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DESIGN AND USE OF ANTI-G SUITS AND THEIR ACTIVATING VALUES IN WORLD WAR II

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AIR MATERIEL COMMAND
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DAYTON, OHIO

ARMY AIR FORCES TECHNICAL REPORT

No. 5433

Design and Use of Anti-G Suits and their Activating Valves in World War II.

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I. Object of This Report.

During and immediately prior to World War II a large amount of research work of military value was performed by many investigators in this and other countries to study the effects of centripetal acceleration on man. One important outgrowth of this work was the development of anti-G suits to protect man against effects of increased positive G. Now that the war is over and personnel in Army Air Forces research laboratories are likely to undergo changes, it is desirable that a review of this work on anti-G equipment be presented in the hope that it will prove useful to future research workers in this field. The purposes of this report are to summarize present information on anti-G suits and associated equipment which have been developed to date, to present the general conclusions available at this time as to the relationship between the design of a G suit and its efficiency, and to suggest patterns for future research work in this field.

II. Summary.

The maneuverability of a fighter airplane is limited by the tolerance of its pilot to acceleration. The pilot who can withstand higher G forces with clear vision and brain than his adversary has the advantage in combat. Exposure to positive G of sufficient magnitude and duration produces visual impairment and even unconsciousness. Five G if maintained from 7 to 10 seconds produces blackout in the average young man. A pilot can raise his G tolerance by muscular straining and crouching, but this is fatiguing and distracting. Anti-G suits have been devised to raise the pilot's G tolerance and decrease the fatigue resulting from repeated exposures to positive G, thus increasing his combat efficiency. All anti-G suits devised to date operate by applying pressure to the lower parts of the body during increased positive G. Such pressure increases return of blood to the heart and enables the heart to maintain blood pressure high enough to pump blood, grown heavier as a result of the acceleration, to the head at G levels higher than is possible when no G suit is worn. One, the Canadian Franks Flying Suit, utilizes hydrostatic pressure from water encased in the suit to apply the pressure. The rest are pneumodynamic and contain air bladders which are automatically inflated during positive G. Automatic inflation is controlled by a G-activated, G-compensated valve. An average visual protection of 1.0 to 1.5 G is afforded by G suits currently in use. Several types of suits and several air-metering valves are described in this report. The factors involved in the protection afforded by G suits are discussed. The pressure source for anti-G suits in conventional airplanes is the vacuum instrument pump; in turbo-jet airplanes, the compressor discharge of the jet engine. These and other possible sources are discussed. Evidence is adduced to show that the protection afforded by present day anti-G suits does not <u>of itself</u> lead to overstressing of aircraft. Finally, recommendations are made for future research work which can profitably be carried out in the field of G protection.

III. Introduction.

A. Physical principles involved in acceleration.

1. Types of acceleration. Velocity is a vector quantity, and to state the velocity of a body both its speed and direction must be described. Acceleration means a change in velocity and may be a change in speed, direction, or both speed and direction of movement. For practical purposes in aviation acceleration may be classified as linear, angular, and centripetal. Linear acceleration refers to a change in the speed of a body while the direction of movement remains constant. When speed is increased, this change is termed linear acceleration; when it is decreased, linear deceleration. Examples of such accelerations which occur in flying are take-off and landing, catapult take-off, crash landings, parachute openings, and parachute landings. Angular accelerations are changes in the rate of rotation of an object rotating about an axis. Examples are spins and tumbling in free fall parachute jumps. Neither linear nor angular accelerations will be considered further in this report. Centripetal acceleration is that which occurs when the direction of motion of a body is changed. In aircraft, it is the acceleration which occurs in curved flight. The G suit is designed to alleviate the symptoms resulting from this type of acceleration. Hence it is of primary concern in this report.

2. Centripetal acceleration. Newton's first law of motion states that a moving body tends to travel in a straight line until it is acted upon by an unbalanced force. Accordingly, a body will not move around a curve unless a lateral force is exerted upon it. The force which causes a moving body to follow a curved path is directed toward the center of the circle being described by the object at a given moment and is called centripetal force. As stated in Newton's third law, for every action there is an equal and opposite reaction. The term, "action", means the force which one body exerts on a second body, and "reaction" means the force which the second body exerts on the first. When a body, in response to centripetal force pursues a curved path, it exerts an equal force in the opposite direction. This reactive force is termed "centrifugal force". An unbalanced force expressed on a body always produces acceleration. The centripetal force acting upon a body in circular motion continually accelerates it toward the center of the circle. The magnitude of this acceleration is expressed by the following formula:

$$a = \frac{v^2}{r}$$

where, in English units, a = the acceleration in ft/sec^2

v = the tangential speed in ft/sec

r = the radius of the circle in feet

Thus centripetal acceleration is directly proportional to the square of the speed and inversely proportional to the radius of the circle (Figures 1 and 2).

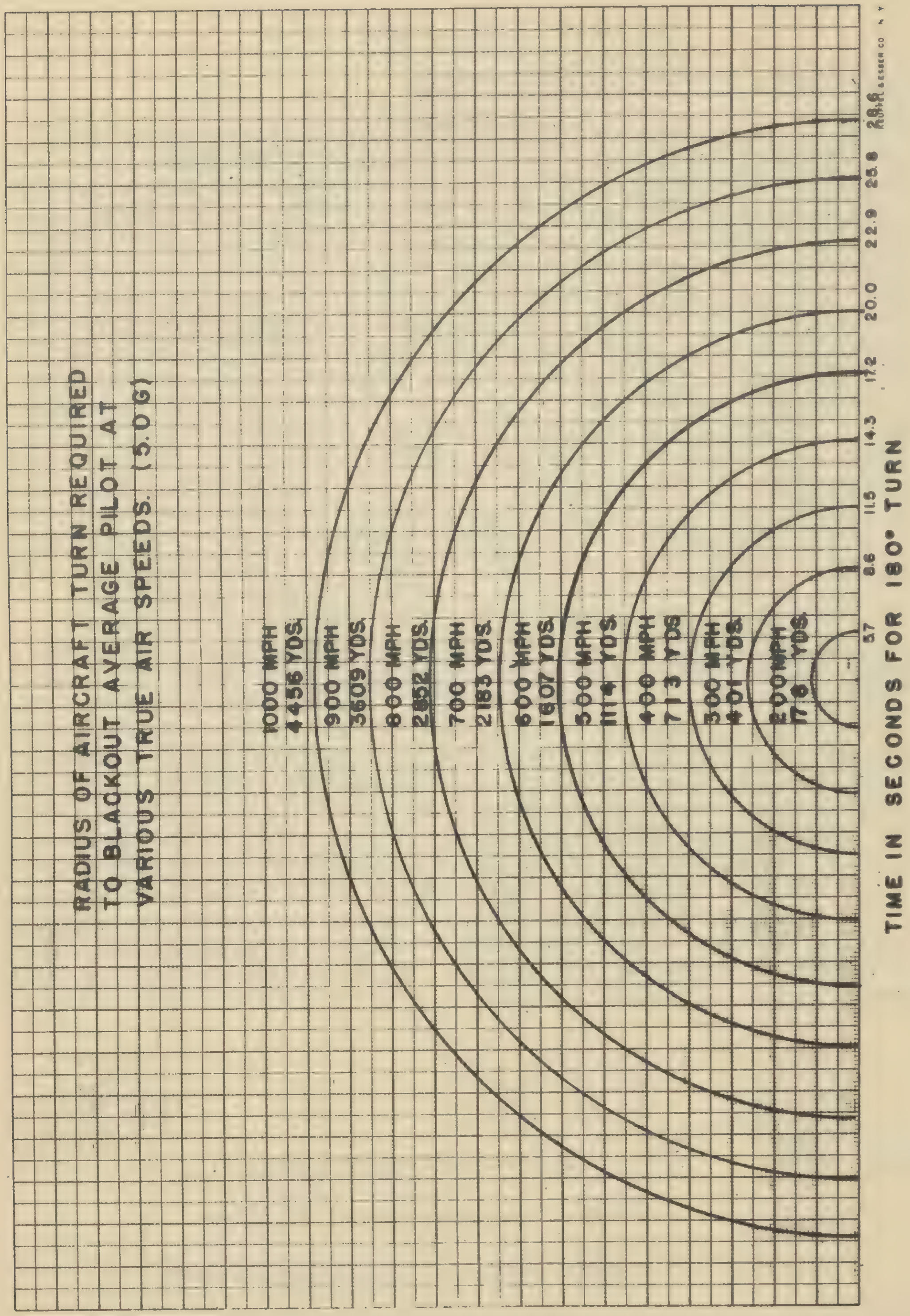
RADIUS OF AIRCRAFT TURN REQUIRED
TO BLACKOUT AVERAGE PILOT AT
VARIOUS TRUE AIR SPEEDS. (5.0 G)
1000 MPH
4456 YDS.
900 MPH
3609 YDS.
800 MPH
2852 YDS.
700 MPH
2183 YDS.
600 MPH
1607 YDS.
500 MPH
1114 YDS.
400 MPH
713 YDS.
300 MPH
401 YDS.
200 MPH
178 YDS.
5.7
8.6
11.5
14.3
17.2
20.0
22.9
25.8
28.6
TIME IN SECONDS FOR 180° TURN

FIGURE I

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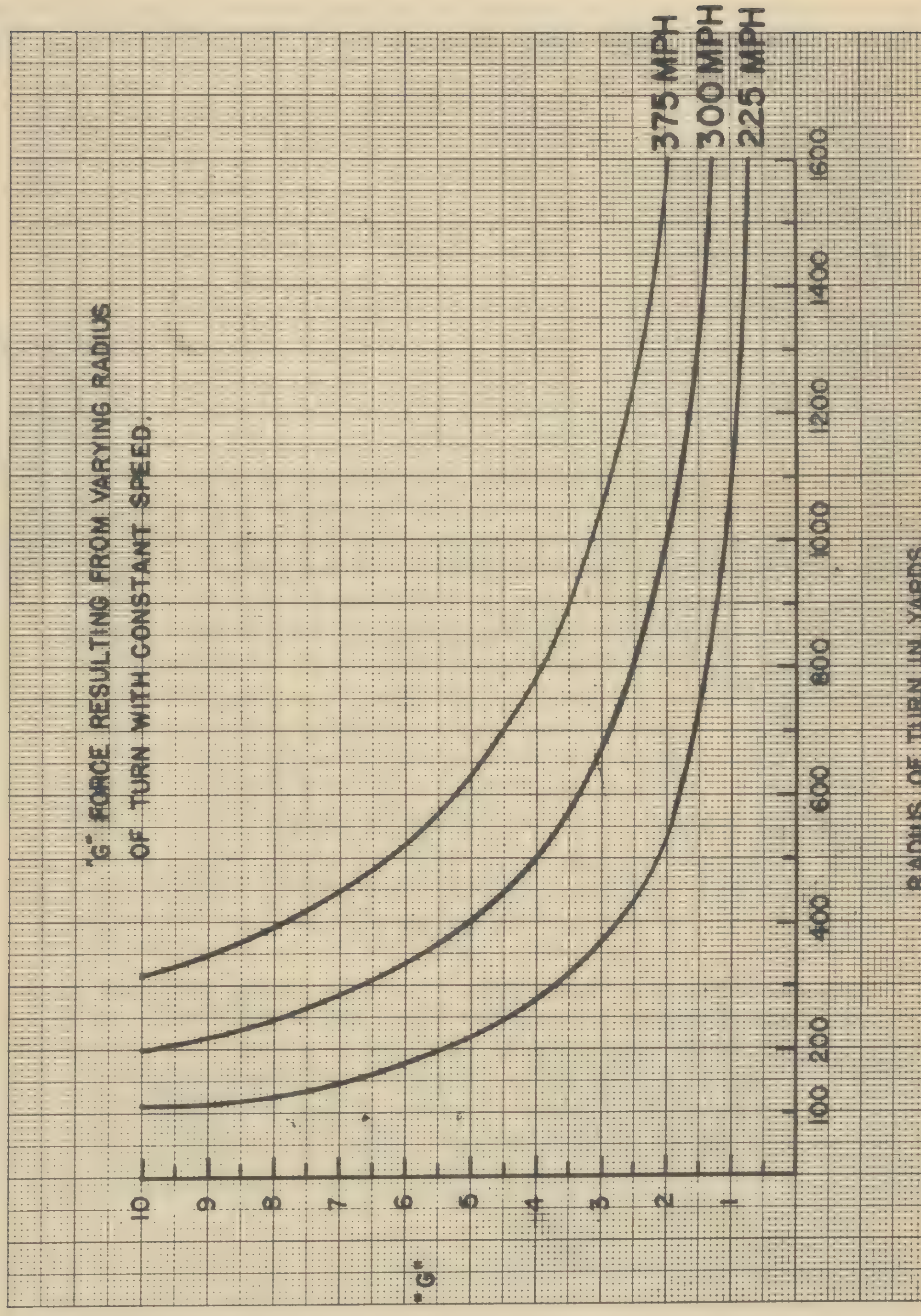

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WRIGHT FIELD

FIGURE 2

Since the tangential speed, v, equals the circumference of the circle multiplied by the number of revolutions per unit time, the formula may be written

$$a = \frac{(2\pi rN)^2}{r}$$

$$= 4\pi^2 rN^2$$

where a = the acceleration in ft/sec^2

r = the radius in feet

N = the number of revolutions per second

3. The G unit. If an object in the earth's gravitational field is allowed to fall freely in a vacuum so that its progress is not impeded by the force of air resistance, it is accelerated at a rate of 32.2 feet/sec^2 (9.8 m/sec^2). This acceleration is caused by the force of attraction which the earth exerts on the body, the force of gravity. This acceleration due to gravity is for practical purposes the same for all freely falling bodies regardless of their mass. For convenience the magnitude of a given rate of acceleration is commonly indicated by comparing it to acceleration resulting from gravity. Acceleration produced by gravity is assigned the value 1 G and is 32.2 ft/sec^2. An acceleration of 10 G is 10 times that caused by gravity or 322 ft/sec^2. Thus

$$a \text{ (in G units)} = \frac{v^2}{rg}$$

where, in English units, v = speed in ft/sec

r = radius of turn in feet

g = 32.2 ft/sec^2

4. Weight and mass. The weight of a body in the ordinary sense of the word is the force of attraction which the earth exerts on it and is therefore determined by the force of gravity. Mass is the term applied to the quantity of matter in the body. A given mass has a certain weight in the earth's gravitational field at 1 G but will have a different weight if subjected to a different force which in turn produces a different rate of acceleration. At 10 G a given mass will weigh ten times its weight at 1 G. This principle forms the basis for design of G-activated and G-compensated valves to be discussed in a later section.

B. <u>Effects of centripetal acceleration on man.</u> The effects of centripetal acceleration on man are determined by (a) its direction with respect to the body, (b) its magnitude, and (c) its duration.

1. Terminology descriptive of direction of acceleration.

a. Aeronautical engineering terminology relates the direction of acceleration or load factor to the aircraft. The centripetal acceleration which occurs in inside turns and which is perpendicular to the thrust line in the direction of normal lift is termed positive G or normal acceleration. Centripetal acceleration in the opposite direction, as occurs in push-down maneuvers and outside turns, is termed negative G. Linear acceleration and deceleration as occur in take-off and in braking at landing, are termed longitudinal load factors or accelerations. Side to side accelerations which may occur during slipping in imperfect turns are termed transverse accelerations.

b. Physiologists, considering the problem from the point of view of the flier, have come increasingly to think of the direction of acceleration in reference to the body of the man. In this sense, acceleration may be in the direction of the long axis of the body or perpendicular to that axis. The term positive G is applied to acceleration in the long axis of the body in the direction of seat to head. Thus the reactive force, centrifugal force in the case of curved flight, acts in the opposite direction of head to seat. The reverse is called negative G. Acceleration in directions perpendicular to the long axis of the body is called transverse G. Depending on the attitude of the body, a given acceleration may have both a transverse and a positive or negative component.

c. Since the position of the flier's body may vary from aircraft to aircraft, some confusion is inevitable between terminologies one of which relates direction of acceleration to the airplane and the other to the human body. When the pilot is seated upright in the conventional position, no confusion exists if both longitudinal and transverse G from the point of view of the aircraft are considered transverse G from the point of view of the pilot. Positive and negative G are the same in both cases. As an example in which confusion can exist, consider the case of the pilot in the prone position. Here positive or negative G from an engineer's standpoint produce transverse G for the pilot. It follows that the meaning of terms indicating direction of acceleration must be clearly stated in cases in which any possibility of confusion exists.

2. Effects of increased positive G on man.

a. The pilot, sitting in the conventional position in an airplane, is subjected to increased positive G in pullouts and banking turns. He is forced down into his seat as he becomes effectively heavier, and the soft tissues of his body are pulled downward.[62] The structural parts of the body of a seated man adequately withstand the accelerations up to 8 or 9 G which may occur in present day fighter aircraft. More important are symptoms referable to the eyes and brain. With successive increases in the centrifugal force there occur dimming of vision, narrowing of the visual field ("tunnel vision"), blackout (loss of vision with preservation of consciousness, though loss of mental acuity and judgment is common), and finally unconsciousness. Recovery from blackout and the stages which precede it require only two seconds or less once the force has abated. Recovery from unconsciousness induced by increased positive G may require as long as 20 to 40 seconds during which time the individual is completely disoriented, and is followed by a period of confusion lasting a minute or longer.

The extreme hazard of unconsciousness resulting from positive G in aircraft is obvious.

b. These symptoms result from lack of oxygen supply to the light-sensitive parts of the eyes (retina) and to the brain, caused by a temporary diminution or even cessation of blood flow through these parts. Blood flow through those parts is compromised for at least two reasons. (1) With the subject in the sitting position positive G acts in a direction parallel to the principal arteries which conduct blood from heart to head. Centrifugal force in positive G opposes the flow of blood in this direction. A given blood pressure at heart level, which may be sufficient to drive blood at 1 G a distance far greater than the 25 to 30 centimeters between heart and head may be insufficient to drive blood grown heavier during increased G through that distance. To illustrate the point, let us assume a sitting man with a column of blood 30 cm. in length between heart and brain. Taking the specific gravity of blood to be 1.058, this column of blood will have a hydrostatic pressure of 23.3 mm. Hg at heart level at 1 G. At 5 G, with the blood effectively five times heavier, this hydrostatic pressure at heart level will be 116 mm. Hg; at 6 G, 140 mm. Hg. Let us assume the systolic blood pressure at heart level, the peak pressure reached during a heart beat, to be the commonly seen figure of 120 mm. Hg. It will follow that the heart under these conditions would be unable to pump blood to brain level at slightly over 5 G, pressure drop due to line friction being disregarded. (2) Secondly, venous blood returning to the heart from the lower parts of the body must do so against the centrifugal force associated with positive G. Some of this blood tends to pool in the dependent parts of the body, a fact which would be expected to diminish the volume of blood returned to the heart per unit time and put the heart at a further disadvantage. X-ray studies of the heart during increased positive G show that the heart shadow becomes elongated and much less dense, indicating a diminuation in the volume of blood contained therein. The evidence as to the relative importance of the roles of diminished return of venous blood to the heart and of increase in the arterial blood pressure required to pump blood to head level is still incomplete. Two facts may be mentioned which speak for the greater importance of the latter: The fall in systolic blood pressure at heart level is relatively minor, being in the range of 6 mm. Hg per G; and blood pressure at heart level recovers and actually increases to levels greater than control values after 7 to 10 seconds of exposure to a given G level.[60]

c. The fluid within the eyeball is under a pressure of 18 to 20 mm. Hg. This pressure must be overcome before blood can enter vessels within it to supply the light-sensitive retina. The brain has no such internal pressure, in fact the pressure within the cranial vault is less than ambient pressure at 1 G and becomes more negative during increased positive G.[22] Hence visual symptoms, which evidence indicates are referable to depleted blood supply to the retina, occur at lower G levels than unconsciousness.[50]

d. The most complete studies of human tolerance to positive G have been carried out on centrifuges (Figure 3). One such study,[17] made on the Air Technical Service Command centrifuge at Wright Field, in which maximal G for a given exposure was attained in two to three seconds and maintained for 10 seconds, yielded the following results: 75 per cent of 35 subjects experienced visual dimming at 3.5 to 4.0 G. The total range for dimming was 3.0 to

HUMAN CENTRIFUGE

AERO MEDICAL LABORATORY ENGINEERING DIVISION
ATSC WRIGHT FIELD

FIGURE 3

5.5 G. Narrowing of the visual field to an arc of less than 46 degrees occurred on the average at 4.4 G with a range of 3.0 to 6.5 G. The average value for blackout was 5.0 G with a range of 3.5 to 7.0 G. Unconsciousness is usually seen at G levels 0.5 to 1.0 above those which produce blackout. Thus there is a great deal of variation in G tolerance between members of a group of individuals. A single individual, studied repeatedly over a year's time is found to preserve a rather constant response, usually varying less than 1 G at any symptom level. These data are valid only for subjects sitting bolt upright and remaining as relaxed as is possible under the circumstances. The habitual crouching of the pilot, which reduces his heart-brain distance, the muscular straining and the nervous tension often accompanying flying tend to raise these values in actual flight. Indeed, properly executed muscular straining may raise tolerance as much as 2 or 3 G.

e. No discussion of G tolerance is complete without consideration of the duration of the force. From four to six seconds are required for development of symptoms. Therefore G values higher than those quoted above may be withstood if their duration is brief enough. For example, a man who will black out at 5 G if it is maintained for 7-1/2 to 10 seconds can successfully withstand 9 G if he can reach that peak and return to lower G levels in a total of approximately four seconds. Thus the warning effect of visual symptoms does not necessarily act as a protection against overstressing an aircraft in snap pullouts. Still another phenomenon related to the duration of G force is the ability of the body's cardiovascular system to compensate for such forces after six to seven seconds exposure. During the first six or seven seconds of exposure to a given force the body is in a state of progressive cardiovascular failure with falling blood pressure and consequent impairment of blood flow to the head. Following this there occurs a reversal of these changes to a greater or lesser extent, depending on the individual, with resulting improvement in any visual impairment which may have occurred. Indeed, it can be said that the most severe symptoms which will occur in a relaxed subject during an exposure of 60 seconds duration to a given G value will occur during the first 10 to 12 seconds.

3. Effects of negative G and transverse G on man. Though in this report, dealing as it does with G suits and valves, primary interest centers about positive G, brief mention of effects of negative and transverse G are worthwhile to complete the introductory review of the effects of centripetal acceleration on man.

a. Man's tolerance to negative G is much lower than that to positive G. Values of minus 2 to minus 3 G produce fulness and throbbing pain in the head. The vessels of the eyes are congested and reddening of vision may occasionally occur. At levels of minus 3 to minus 4 G there is danger of hemorrhage in the brain with brain damage or even death. As a consequence, negative G is commonly avoided by initiating sudden descents by "peeling off" maneuvers instead of push-down maneuvers.

b. Assumption of the prone or supine positions translates positive or negative G considered relative to the airplane to transverse G relative to the human body. Blood can course from the lower extremities to the heart and from

and from heart to head in a direction perpendicular to the increased force, and visual symptoms are prevented. Bührlen in Germany[24] noted that subjects in the recumbent position exposed to centrifugal force in an antero-posterior direction relative to the trunk (supine position) on a centrifuge experienced no symptoms other than slight respiratory difficulty up to 10 G. Above 10 G, respiration became increasingly difficult, and above 15 G breathing was almost impossible. One subject reached 17.3 G without visual impairment. Similar results have been obtained with the prone position in centrifuge tests by Armstrong and Heim,[1, 2] Wood, Code, and Baldes,[58] and Clark et al.[43] Needless to say, practical use of the prone position will demand that the head and shoulders be raised approximately 15 degrees to promote adequate vision. With the head thus slightly above heart level, visual symptoms will occur at high G levels. Clark et al observed occasional visual dimming at 12 G which could be made to progress to blackout if the head was raised slightly when subjects were supported on a stage which would be feasible from the viewpoint of control of an airplane. The prone position is difficult from an engineering standpoint because: (1) the head must be supported by some means both at 1 G to avoid fatigue of the neck and at increased G to avoid injury, (b) visibility is limited, and (c) a rather radical change in bodily coordination must be learned by the flier. None of these obstacles is insuperable. The supine position has been approached by the use of tilting seats. One body of data from the Mayo Aero Medical Unit indicates that tilting back to an angle 30 degrees from the horizontal raises blackout threshold by approximately 1.5 G and gives greater protection against unconsciousness.[34] Use of a crouch position in which the pilot leans forward, thus shortening his heart-brain hydrostatic distance, was found at the RCAF centrifuge to raise G tolerance an average of 2.7 G (Figure 4). Elevated rudder bars to raise the feet and shorten the fluid column between heart and feet have been stated to give slight protection.

C. <u>Methods of protecting man from effects of positive G.</u> From the foregoing, an outline of methods of protection against effects of centripetal acceleration can be formulated. The following is adapted from one suggested by the Mayo Aero Medical Laboratory:[45]

1. Mechanical protection.

   a. Protective postures.

      (1) Supine or semi-supine.

      (2) Prone or semi-prone.

      (3) The crouch.

      (4) Elevated rudder bars.

   b. Protective suits, applying pressure to the lower parts of the body and functioning by elevating blood pressure due to a combination of

      (1) Increasing return of blood to the heart, and

      (2) Increasing arterial peripheral resistance.

Data from Accelerator Section, No. 1 Clinical Investigation Unit, R.C.A.F.

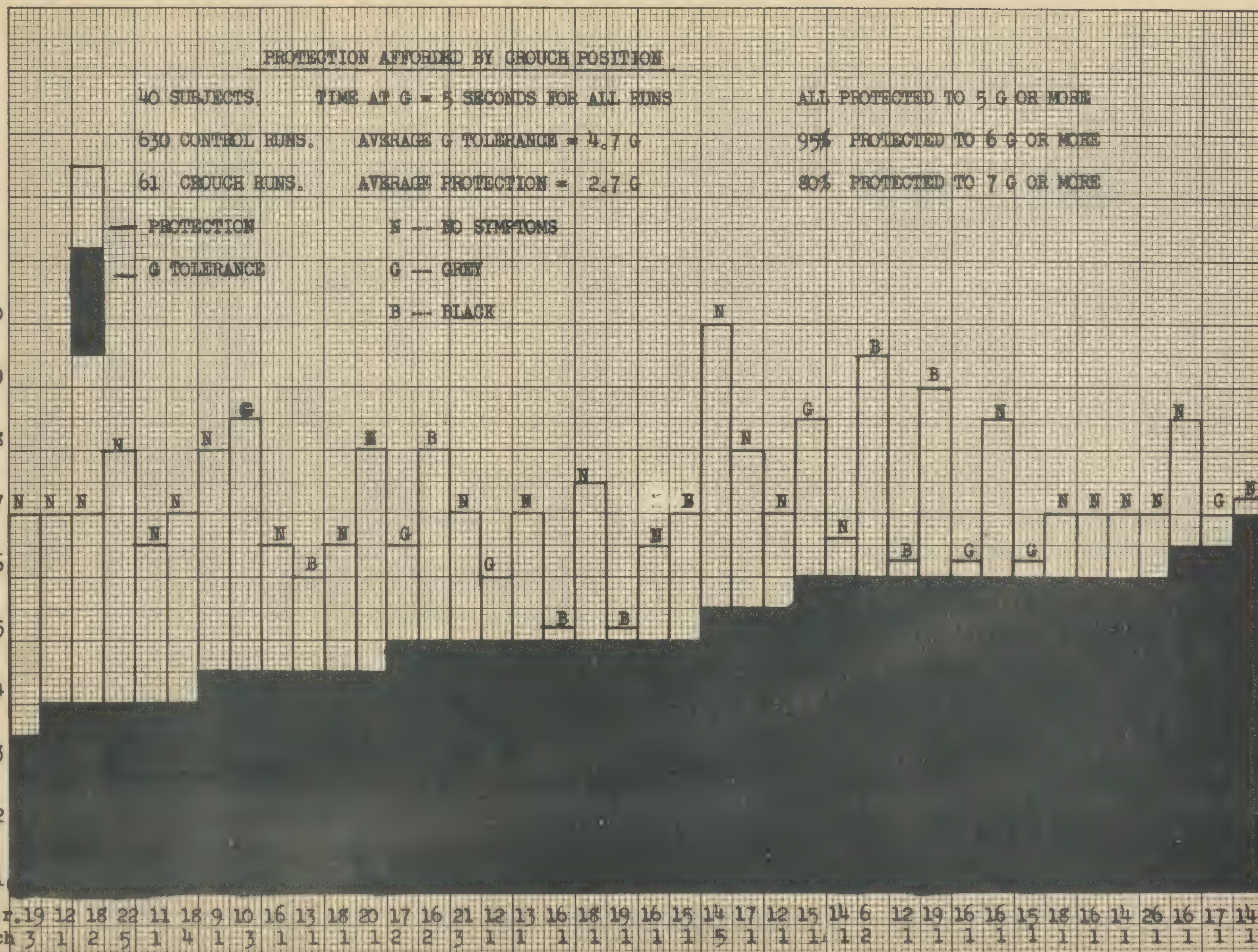

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FIGURE 4.

2. Physiological self-protection.

   a. Pressor reflexes induced by accleration, i.e., cardiovascular compensation.

   b. Self-induced pressor reflexes, such as those causing the elevation of blood pressure and consequently of G tolerance which results from properly performed muscular straining.

   c. Increase in G tolerance said to follow ingestion of a meal.[26]

3. Pharmacodynamic protection.

   a. Though little work has been done in this field in the human, the possibility remains that a drug may be found which raises G tolerance. Benzedrene in a dose of 10 mg. does not accomplish this.[15] Breathing CO_2 has been observed to raise G tolerance approximately 0.5 G.[25]

IV. Anti-G Suits (Anti-blackout Suits; Pilots' Pneumatic Suit, Anti-G).

A. General requirements for anti-G suits. The following general requirements for anti-G suits can be set up as goals to be sought in design of this equipment. Different types of devices to be described later in this section can be appraised according to the degree to which they measure up to these requirements.

1. The total weight penalty for the aircraft should be no more than five pounds.

2. Action of the device must be entirely automatic.

3. In order to obtain acceptance by pilots, the device must produce a minimum of discomfort. It must allow freedom of bodily movement both in the aircraft and in ordinary wear on the ground. It must not be tight fitting in level flight and must not be hot. The pressure applied to the body during increased G must be tolerable and evenly distributed to avoid points of discomfort.

4. Any connection which connects a pilot's suit to equipment in the aircraft must be capable of simple, rapid and certain release.

5. Appearance of a G suit should approach that of ordinary flying clothing as much as possible. The ideal would be a garment entirely suited for routine wear whether G protection is needed or not, but which provides G protection when the requirement arises.

6. G protection must be adequate to allow the pilot to exploit the full capabilities of his aircraft without raising G tolerance to a point that overstressing of the airplane is encouraged. The numerical value of the G protection needed depends on the method of evaluating protection offered by a given suit. This will be the subject of the next paragraph.

B. Methods of appraising G protection afforded by anti-G devices:

1. The human centrifuge provides the logical means of carrying out preliminary comparative tests on anti-G devices because of the safety and close control of subject and acceleration which it provides. In general in each acceleration laboratory on this continent the efficiency of a given anti-G device has been appraised by (a) establishing a standard test run with respect to time required to reach maximal G and duration of maximal G and (b) comparing the magnitude of acceleration required to produce some definite measurable effect on the human when the device is not in use to that required to produce the same effect when the device is functioning. Thus, the procedure is a bio-assay and the effect of acceleration chosen as a basis for comparison may be properly termed an end-point.

2. The simplest end-point and the one most consistently used throughout the various acceleration laboratories is that of visual status. Visual status is determined by response of the subject to light signals which flash on a panel in front of him. At the RCAF centrifuge at Toronto, Canada, a light signal is

given to the subject at varying intervals by an observer riding near the center of rotation. The subject signifies that he can see it, if he can, by means of signal lever on the side of the dummy control stick. The subject also signifies his subjective impression of the onset of visual dimming and duration of blackout by a button on top of the stick.[23] In assays of protection afforded by a G suit the RCAF laboratory uses the blackout threshold as its end point and defines blackout threshold as the lowest G which when applied for five seconds in a standard force-time pattern produces blackout. In the American centrifuges lights on the panel in front of the subject are turned on by the observer (or by an automatic cam driven switch) and turned off by the subject if he can see them. One light is centrally placed at the subject's point of visual fixation; two are located peripherally, one on each side of the central light, so that an angle of 23 degrees is subtended from central to peripheral light with the eyes as a center of the circle. With this system differentiation between clear vision and visual dimming without inability to see the peripherally placed lights depends entirely on the subjective statement of the person being tested. The level of loss of peripheral vision (hereinafter abbreviated PLL for peripheral lights lost) is taken to be the lowest G at which failure to respond to peripheral lights is noted. The blackout level (hereinafter abbreviated CLL for central light lost) is the lowest G at which the subject fails to turn off both peripheral and central lights but does not slump down in unconsciousness and can hear and turn off a buzzer signal which is provided. Commonly, one or more of the following are determined both with and without the anti-G device: (a) the highest G level tolerated with clear vision, (b) the lowest G level which produces visual dimming without PLL, (c) the lowest G level which produces PLL, (d) the lowest G level which produces CLL. Less frequently the lowest G level which produces unconsciousness is noted. In routine tests of anti-G devices, the unconscious state has usually been avoided whenever possible. G protection in G units at a given symptom level is obtained by subtracting the G value obtained without the anti-G device from that obtained when the device is used.[52, 44, 16] Additional end points, advantageous because they provide objective measurements to supplement the essentially subjective responses of the subject to visual stimuli, are based on changes in the ear pulse and ear opacity. A sample record demonstrating these changes is presented in Figure 5. These have been used by the Mayo Aero Medical Laboratory and the University of Southern California Aero Medical Laboratory. In the case of ear opacity, the accelerations which produce similar deflections of the recording galvanometer after five seconds at maximal G and the accelerations which produce similar maximal deflections during maximal G are compared with and without suit inflation. In the case of the ear pulse, the recorded height of the ear pulse during each exposure to acceleration is compared to the height just before the acceleration was applied. The accelerations during the control run at which the height of ear pulse was reduced a half or more but not lost and the acceleration at which the ear pulse was lost are compared with the accelerations at which similar changes in the ear pulse occur when the protective device is used.[52]

3. Methods of recording suit protection measured by the bio-assay technique: In many instances, the protection a suit affords clear vision and its efficacy in preventing visual dimming, PLL, and CLL are all measured. Usually the degree of protection against CLL is greater than that afforded clear vision (Table 1.). Furthermore, the protection afforded different subjects is variable (Figures 14,

Effects of Centrifugal Force on Human Subject

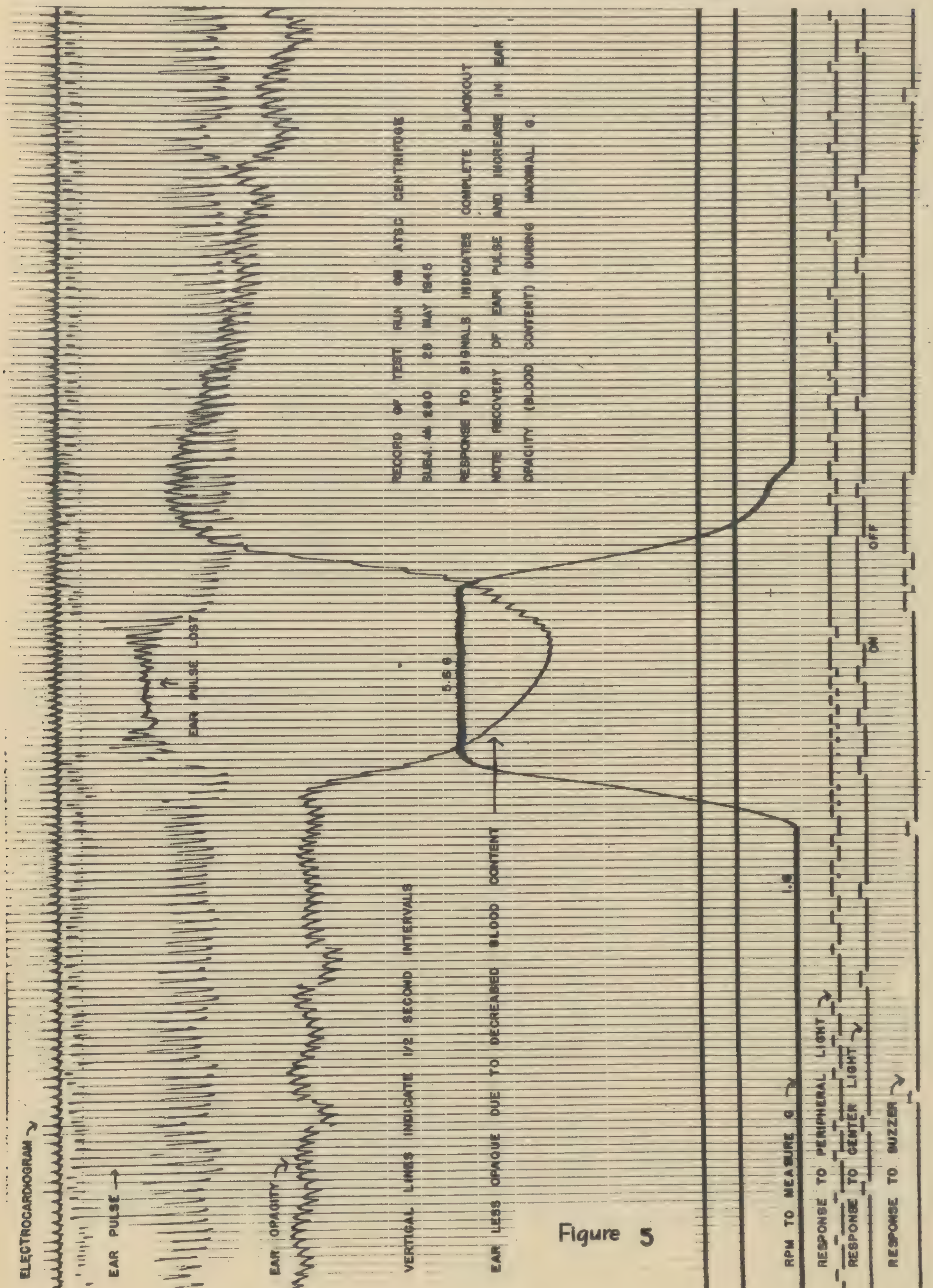

Figure 5

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Table 1.

Centrifuge Studies of G Protection Afforded by Various Anti-G Suits.

Protective Device	Laboratory	Notes	Protection Afforded Vision: Clear N	Clear G	Dim N	Dim G	PLL N	PLL G	CLL N	CLL G	Avg. Visual Protection N	Avg. Visual Protection G	Ear Pulse N	Ear Pulse G	Ear Opacity N	Ear Opacity G	Ref.
Immersion in water	Mayo AML	Water to level of xiphoid process	6	0.6	4	0.5	6	1.4	7	0.9		0.8	8	1.9	12	0.9	59
"	"	Water to level of third rib	10	1.4	4	1.6	8	2.0	8	1.9		1.7	8	3.0	12	1.5	59
Early model FFS	RCAF	Suit extended to heart level							20	2.1							23
Mark III FFS	"								19	1.8							21
"	Mayo AML	With 4.7 liters of water	9	0.6			5	1.2	4	1.2		1.0	4	1.6	10	0.9	59, 52
"	"	Suit filled with water	8	1.0			7	1.4	4	1.9		1.4	2	2.3	9	1.5	59
AOS Model 5	"	Pressurized as in Figure 9		2.5		2.5		2.7		2.6		2.6				2.8	59
GPS AAF type G-1	"	With standard G-1 valve	19	1.1	6	1.4	11	1.6	17	1.5	21	1.3	21	2.2	21	1.7	51
"	ATSC AML	"	19	1.2	12	1.2	17	1.6	11	2.5	20	1.5					7
AAF type G-2	Mayo AML	1.25 p.s.i./G calculated from 0 G	5	1.4	6	1.1	9	1.4	7	1.6	14	1.4	9	1.7	13	1.5	51
"	ATSC AML	1.0 p.s.i./G calculated from 0 G	22	1.2	8	1.2	20	1.3	22	1.9	22	1.4					13
Nylon Bladder Suits, Models 10-17	Mayo AML	1.0 p.s.i./G calculated from 0 G	10	1.7	10	1.9	8	2.0	10	2.2	12	1.9	12	2.5	11	1.9	*

* Minutes Sixth Meeting Committee on Aviation Medicine Subcommittee on Acceleration, 7 June 1944.

Table 1. (Cont'd.)

Protective Device	Laboratory	Notes	Protection Afforded Vision: Clear		Dim		PLL		CLL		Avg. Visual Protection		Ear Pulse		Ear Opacity		Ref.
			N	G	N	G	N	G	N	G	N	G	N	G	N	G	
AAF type G-3	ATSC AML	1.0 p.s.i./G calculated from 0 G	11	1.0	8	1.0	11	1.1	11	1.3	11	1.1					14
"	Mayo AML	"	7	1.1	5	1.1	4	1.1	9	1.3	9	1.2			8	1.1	*
"	"	1.0 p.s.i./G calculated from 1.5 G	9	0.8	4	0.9	8	0.8	9	0.8	10	0.8	10	0.9	10	0.9	39
U.S. Navy type Z-1 (AAF G-4)	ATSC AML	0.86 p.s.i./G calculated from 0 G	10	0.9	4	1.1	8	1.1	10	0.9	10	1.0					14
"	Mayo AML	1.0 p.s.i./G calculated from 1.5 G	13	0.9	8	1.2	14	1.0	16	1.3	17	1.1			17	1.0	63
"	"	1.0 p.s.i./G calculated from 0 G	10	1.4	6	1.5	9	1.4	10	1.6	11	1.4			11	1.4	63
"	USC AML	1.0 p.s.i./G calculated from 1.75 G			10	1.2	16	1.2	17	1.4	29	1.3					42
U.S Navy Type Z-2	"	"	2	1.2	14	1.2	25	1.3	17	1.2	31	1.2			19	1.2	42
"	"	1.5 p.s.i./G calculated from 1.75 G	1	1.3	5	2.4	12	1.5	10	1.3		1.6					42
PLS with Berger abdominal bladder	ATSC AML	Approx. 1.5 p.s.i. per G calculated from 0 G	5	0.9	5	1.0	6	1.1	4	1.7	6	1.2					54
Model L-12 PLS	USC AML	2.2 p.s.i./G starting at 2.0 p.s.i. at 2.0 G	11	1.2	12	1.5	11	1.7	11	1.9	12	1.6					56

* Personal communication from Dr. E. H. Wood.

18, 25 and 27). It has been found convenient and proven practical to compare the efficacy of one suit with another by assigning it an average visual protection, computed by averaging values of protection for clear vision, dimming, PLL, and CLL, and augmenting this by values for protection of ear pulse and ear opacity where these are available. This method will be followed in the text of this report, with details of protection at different symptom levels presented in tables. Therefore in interpretation of these values we should note:

a. That average protection figures do not allow one to predict exactly the protection which will be gained by particular individuals, but are of use in comparing different suits.

b. That the protection at various symptom levels may differ from the average visual protection, being usually greater for CLL and smaller for clear vision.

c. That protection of ear opacity (blood content of the ear) usually compares closely with average visual protection.

d. That protection of ear pulse is usually greater than protection of ear opacity or average visual protection, and may correlate more closely with protection against unconsciousness.

4. If the purpose in assaying the degree of G protection afforded by an anti-G device is to approach knowledge of the protection offered by the device alone, one must control those factors which, if they are allowed to vary, cause G protection to vary or can independently add or subtract from that protection. The following discussion will describe the important variables which require control:

a. The condition of the subject: The first few rides on a centrifuge normally find a subject in a state of excitement with nervous and muscular tension, factors which tend to raise G tolerance and render it variable. Consequantly constant results can be expected only if subjects have been indoctrinated in centrifuge procedure and have overcome the initial apprehension common in early experiences. Complete muscular relaxation, desirable to eliminate variable results which accompany varying degrees of muscular straining, is in the strict sense impossible but a very considerable degree of muscular relaxation can be achieved with practice. Such muscular relaxation is still more difficult during inflation of a G suit, since one's proprioceptive reflexes tend to produce some increased muscle tonus. Indeed, some of the protection afforded by suits undoubtedly results from the muscular tension which they induce. The important point in this regard is that muscular relaxation should be encouraged and purposeful straining prohibited if the basic protection afforded by the suit alone is to be approached. Occasionally subjects will voluntarily or involuntarily stop breathing during centrifuge trials, a maneuver usually associated with straining of abdominal musculature and consequent increase in G tolerance. Subjects should be encouraged to maintain normal respiration throughout runs, and recordings of respiration are useful checks in control of this variable. Recording of intrarectal pressure as a check on the degree of muscular straining carried on by subjects was introduced by the University of Southern California centrifuge group. Since any shortening of the heart-brain

hydrostatic distance raises G tolerance and any variation in this distance causes variation in the response at a given G level, the position of the head must be fixed. This is accomplished by providing a head rest and requiring subjects to sit upright with head touching the head rest throughout the tests.

b. Certain environmental factors must be kept constant. G tolerance varies inversely with environmental temperature.[46] Accordingly, it is important to stabilize room temperature during comparative tests.

c. Of prime importance is the force-time pattern of the acceleration employed. Remembering that the minimal time in which symptoms will develop is approximately five seconds and that in many instances six to eight seconds are required[52] one realizes that a test run of too short a duration will mask symptoms simply because insufficient time is allowed for them to develop. Also, the rate at which maximal G is attained must be kept relatively constant since if it is unduly prolonged enough time can be spent at G levels lower than that finally reached to allow physiologic compensation to occur and alter the subject's status during maximal G. Two general types of G patterns have been used on this continent. In the first, used by the RCAF centrifuge at Toronto, five seconds are employed to progress from rest to 1.5 G; five seconds from 1.5 G to maximal G, five seconds are spent at maximal G, five seconds are used to drop to 1.5 G, and five seconds from 1.5 G to rest.[23] Thus an entire run occupies 25 seconds. Test runs used by acceleration laboratories in the United States differ in that maximal G is attained quickly at a rate of approximately 2 G per second and is maintained for a longer time. In routine test runs at the University of Southern California and Mayo aero medical laboratories, maximal G is maintained for 15 seconds; at the ATSC centrifuge both 10 and 15 seconds have been used. Ten second runs are adequate to allow development of symptoms but are short if phenomena of physiologic compensation during increased G are to be studied. The time required for the force to abate is of less importance in these assays, and is often increased to minimize the symptoms of vertigo which accompany rapid angular deceleration.

C. <u>The degree of G protection required in fighter airplanes in World War II.</u> Once a method had been developed for assaying the protective value of anti-G devices it became essential to know what protection, as measured by this method on the centrifuge, should be sought for anti-G equipment to be used in the airplane. As late as 1943, workers in the field of acceleration assumed that an anti-G device, to be useful, should raise G tolerance by at least two or three G. It was felt that this protection would permit an unprotected man who blacked out at 5 G to safely reach 7 or 8 G, figures nearing but still beneath the supposed stress limits of available aircraft. At that time no data had been collected in aircraft which disagreed with this conception. During aircraft tests in P-40, P-47, and P-51 aircraft at Eglin Field in October-November 1943 it became evident that a suit which gave between 1.0 and 1.5 G protection in centrifuge tests was quite adequate in these aircraft.[67] In these tests no complete blackout occured though as high as 9 G was reached by pilots wearing the suit. Superficially it appeared as if the suit were giving much greater protection in the airplane than in the centrifuge. There was ample reason to believe that this might be the case, since pilots in flight almost universally engage in some degree of crouching and straining during G producing maneuvers. The problem was clarified by the experiments carried out by Lambert in an

A-24 airplane arranged so that both pilot and passenger could be subjected to increased G with or without protection.[36,37,38,39] The time-force patterns of acceleration in flight were made to conform with the curves used in centrifuge work in order that data from the two sources would be comparable. In both cases, acceleration was attained at a rate of approximately 2 G per second and the maximal G was maintained for 15 seconds. Lambert's data indicated the following:

1. The G tolerance of 24 subjects, measured by the occurrence of visual symptoms, was on the average 0.7 G higher when they were passengers in the airplane than when they were subjects on the Mayo centrifuge:

Airplane						Centrifuge											
Average G level at which symptoms were:						Average G level at which symptoms were:						G units higher in airplane:					
Dim		PLL		CLL		Dim		PLL		CLL		Dim		PLL		CLL	
n	G	n	G	n	G	n	G	n	G	n	G	n	G	n	G	n	G
19	3.9	18	4.2	17	4.6	18	3.4	20	3.6	19	4.0	15	0.6	15	0.7	14	0.8

It is of interest to remember that the average figures for PLL and CLL were 4.4 and 5.0 G respectively in a series of tests made on the ATSC centrifuge, figures only slightly different from thos obtained by Lambert in aircraft tests.[17]

2. The pattern of physiologic changes which occurred during positive acceleration in the airplane was practically identical to that which occurred on the centrifuge, though the sequence of events tended to occur one to two seconds earlier during exposure to acceleration in the airplane. Recovery of vision, the ear pulse, the blood content of the ear, and the pulse rate while the acceleration was still maintained tended to occur earlier and to be more rapid and complete in the airplane than on the centrifuge.[36]

3. The G-4 (Z-1) anti-G suit (described below), which gave an average protection of 1.0 G against visual symptoms in a series of 13 subjects on the Mayo centrifuge, provided an average visual protection of 1.1 G for the same subjects when they were passengers in the airplane[37]

4. The G tolerance of pilots flying the airplane averaged 0.7 G more than that for the same men riding as passengers.[38]

5. The G-3 anti-G suit (described below), which gave a protection of 0.8 G against visual symptoms in a series of 9 subjects on the Mayo centrifuge, provided visual protection of 0.9 G for 12 pilots flying the airplane.[39]

6. These data establish the essential similarity of the effects of positive acceleration and the efficacy of G suits on subjects in the airplane and on the centrifuge. They further indicate that the G tolerance of humans in aircraft is not widely different from that on the centrifuge. Such differences as do exist probably result from several causes: (a) environmental temperature in aircraft was lower in these tests than that in centrifuge work;

(b) subjects, especially when flying the airplane, do not sit as erect in the aircraft as on the centrifuge; (c) the excitement of flying may raise the blood pressure and with it G tolerance. It follows that a potent factor in the observation that protective devices offering only 1 to 1.5 G protection have been adequate in aircraft used in World War II has been the fact that accelerations above 5 G have usually been of too short duration to allow full development of visual symptoms. Indeed, Lambert found that once pilots learned to maintain six to seven G in the aircraft for 10 seconds, visual symptoms became common even though the G suit was worn. This does not render the present suit valueless, however, since these suits combined with purposeful muscular straining will easily permit exposure to eight G or more without significant visual symptoms.[7]

D. Available data on anti-G devices developed prior to and during World War II. Anti-G suits thus far developed can be classified as hydrodynamic or pneumodynamic according to the source of pressure employed. The best developed water suit will be described first, and after it, a series of air suits.

1. The Franks Flying Suit (FFS).

a. Workers in the field of acceleration have long realized that one method of opposing the downward displacement of blood during exposure to positive G would be to surround the pilot's body with a fluid so arranged that the increased pressure which is developed throughout the liquid when the liquid mass is exposed to increased G is transmitted to the body surface. Such a liquid column provides a perfect gradient pressure with highest pressure deep in the fluid at foot level and lowest pressure at the surface at chest level. The actual pressure at any level depends on the magnitude of the G and on the specific gravity of the liquid. A German view on the subject is quoted from Ruff and Strughold's Compendium of Aviation Medicine (1939):[26] "A particularly appropriate measure to hinder this dislocation of blood would be to surround the body with a fluid which possesses a specific gravity as similar as possible to that of the tissues and fluids of the body and which, upon increase of its pressure, cannot distend. It has been proposed to surround the body up to the neck with a double walled suit, of which the outer wall is indistensible and the inner distensible, adjusted closely to the body surface. In case of acceleration the changes of hydrostatic pressure in the suit and in the organism would oppose each other. However correct these technical considerations, this is a somewhat difficult matter to put into practice. The weight of the suit alone, as well as the hindrance to the movements of its wearer, would interfere with its effectiveness."

b. In 1943 the Mayo Aero Medical Laboratory undertook a series of experiments to determine the degree of G protection afforded the seated human subject by immersion in water. A bathtub-like container of sufficient size to accommodate subjects was placed in the cockpit of the Mayo centrifuge. Experiments were performed with the water level in the tub at the level of the xiphoid process and at the level of the third rib. Results are shown in Table 1. Immersion in water to the level of the xiphoid process afforded an average protection of 0.8 G against the occurrence of visual symptoms. Immersion in water to the level of the third rib provided an average visual protection of 1.7 G.[59] This degree of protection can be taken to be the maximum to be

afforded by a water suit if no auxiliary straining or crouching is used.

c. The problem of making a water suit was undertaken by Wing Commander W. R. Franks, RCAF, and his associates, who, after a great deal of study, developed the beautifully designed Franks Flying Suit (Figure 6). The following brief description of the device was written by Franks in 1941.[32] "1. An intercommunicating fluid system, encased in rubber units, is interposed between the body surface and a close fitting garment made of non-extensible yet flexible fabric. During a maneuver a hydrostatic pressure is brought to bear on the surface of the body, which automatically equalizes the internal pressure built up in the fluids of the body by the accelerating force. 2. Former experience in aircraft showed that a considerable degree of protection was obtained by covering the body hydrostatically from the level of the heart down. The return blood supply to the heart is then assisted and the blood flow to the brain can be maintained at higher accelerations than otherwise. The shoulders and arms are consequently left free in the present suit. 3. The fluid containing units do not cover the whole body, but are placed in certain areas only, in contrast to the outer fabric, which is complete below heart level. Areas not covered (by fluid containing units) receive their protection automatically from tension built up in the outer fabric by hydrostatic pressure in the fluid units of the parts covered."

d. The protection afforded by the FFS on the centrifuge has been determined by the Canadian group at Toronto and by the Mayo group at Rochester, Minnesota. Data from two series of experiments performed by the RCAF are shown in Table 1. The method employed compares blackout thresholds of subjects with and without the suit. In the two series, one including 20 and the other 19 subjects, the blackout threshold was elevated 2.1 G by an early suit which covered the body well above heart level (Figure 7)[23] and 1.8 G by the Mark III FFS which came to the level of the lower ribs.[21] The Mayo data for the Mark III FFS indicate an average visual protection of 1.0 G when the suit contained 4.7 liters of water and 1.4 G when it was filled to the brim.[59] It should be noted that only the Mayo data on protection against CLL are at all comparable to the Canadian data. These figures, based on four subjects are 1.2 G with 4.7 liters of water and 1.9 G when the suit is completely filled (Table 1). Reference to Table 1 also indicates that the G protection afforded by immersion in water corresponds fairly closely with that afforded by the FFS with varying amounts of water. The FFS makes efficient use of the hydrodynamic principle for providing G protection.

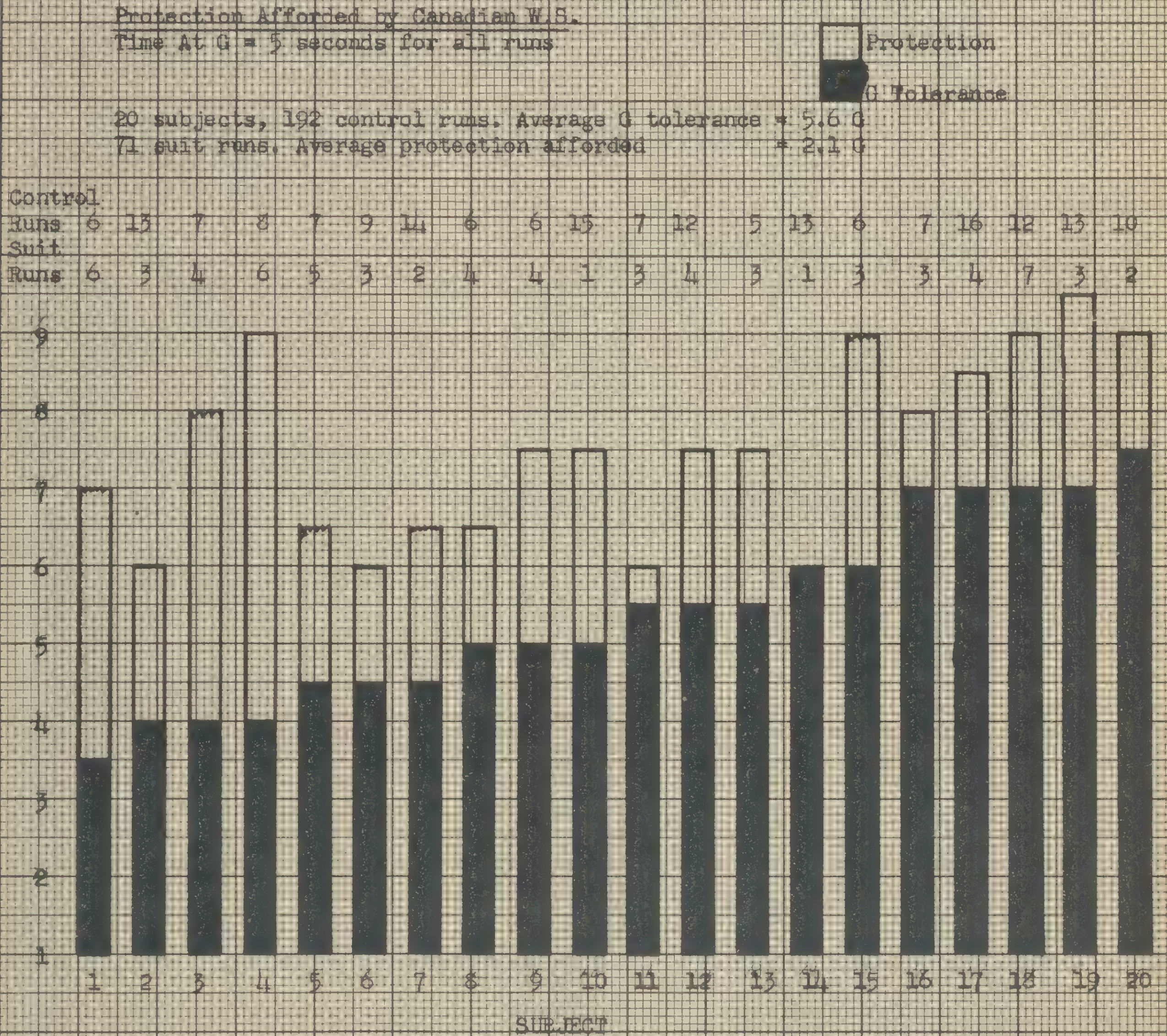
e. Wing Commander Franks and his assistants have also experimented with the use of a combination of air and water pressure in the FFS, air pressure being furnished when a large bellows was compressed by the increase in weight during G of an aircraft battery mounted atop it. This combination was designated the AB/BG system.[21] Since the available volume is limited by the size of the bellows, pressure developed in the suit depended on the percentage of space therein which was filled by water. With this sytem it was found that the blackout threshold was raised 0.9, 1.1, 1.5+, 2.0+ and 2.5+ G respectively as the water level in the FFS was raised from ankle to heart level (Figure 8).

f. Extensive flight tests have been performed with the FFS.[27,28,29,30,32] An historical summary of these will be found in FPRC Report No. 584.[30] In one

FRANKS FLYING SUIT
(WATER SUIT)

NOTE WATER INLET TUBE IN FRONT OF UPPER ABDOMINAL SECTION AND DRAINS ON EACH LEG SECTION.

FIGURE 6



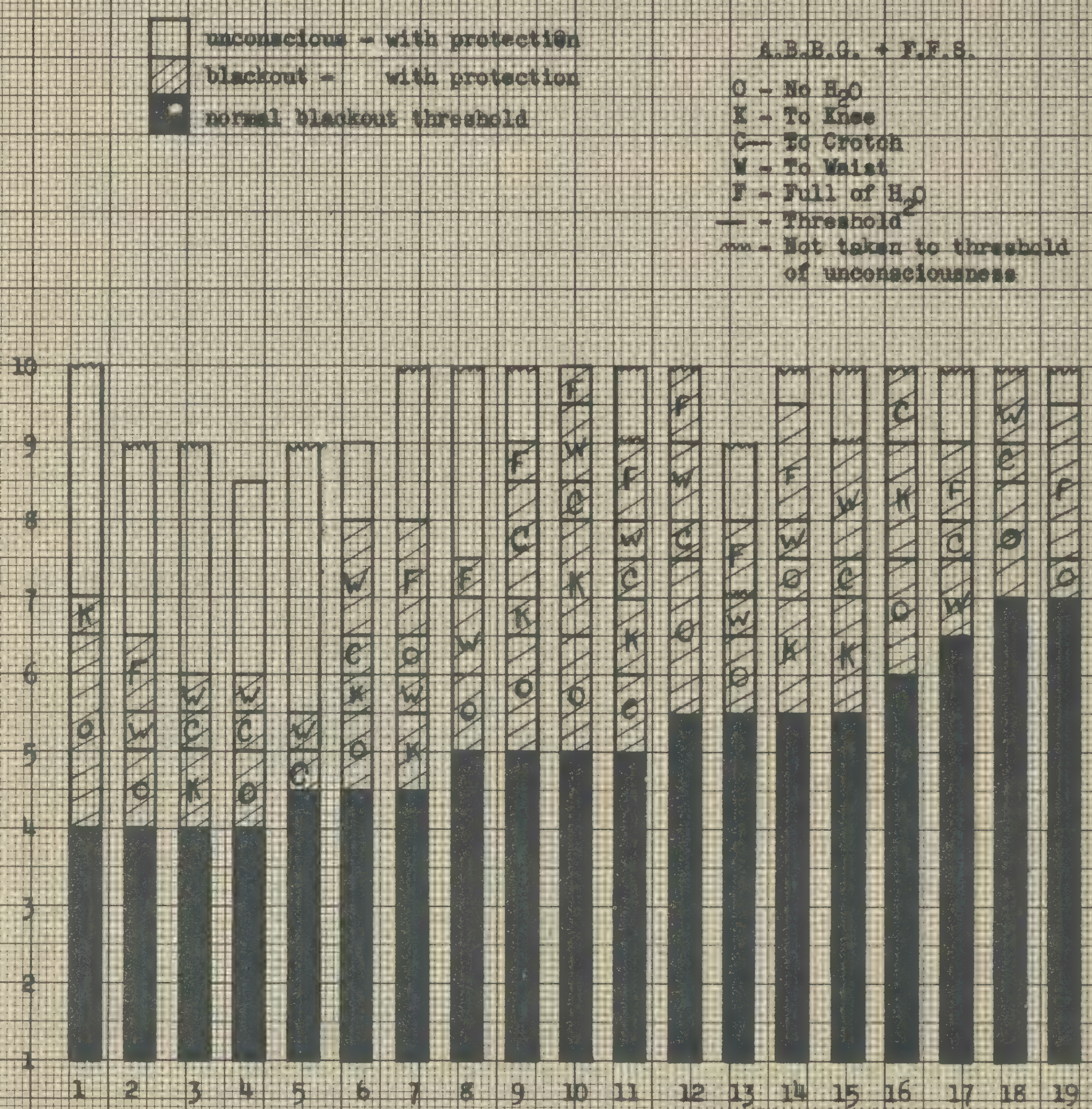
In the above figure each column represents a subject. The ordinate is given in G. The solid black portion of each column indicates the blackout threshold of the respective subjects, the clear upper portion of the column indicates the blackout threshold of the same subject when wearing an F.F.S. Above each column the number of control runs and the number of suit runs are given for each subject. The average protection afforded was 2.1 G.

From Accelerator Section, No. 1 Clin. Investigation Unit, R.C.A.F., Report No. 9 to Ass. Com. on Avn. Med. Research, N.R.C., Canada dated 1 Sept 1943

5433

FIGURE 7.

PROTECTION AFFORDED BY AEBG + FFS



In the above figure each column represents a subject. The ordinate is given in G. The solid black portion of each column indicates normal blackout threshold and the shaded portion the blackout threshold with F.F.S. filled with air and various amounts of water. The clear upper portion indicates unconscious threshold.

From Accelerator Section, No. 1 Clin. Investigation Unit, R.C.A.F., Report No. 13 to Ass. Com. on Avn. Med. Research, N.R.C., Canada dated 28 Sept 1944

FIGURE 8.

series in which 66 pilots participated, G protection was stated to be 1.5 G, ascertained by the use of visual accelerometers in the aircraft. Thirty-four pilots (64 per cent) stated that use of the suit reduced fatigue; 19 (36 per cent) stated that it did not.[29] The conclusion of the Royal Air Force was summarized as follows: "It was the almost unanimous opinion of the pilots as a result of these trials (a) that although the suit does provide the advantages claimed for it, they are outweighed by its disadvantages in the air and on the ground, and (b) that the FFS Mark III is therefore not practicable to use under Tactical Air Force conditions as represented on this airfield."[29] Thus although the FFS is entirely automatic and requires no installation in the aircraft and although it performs the function for which it was designed, it failed to obtain general acceptance by pilots because of its weight, bulk, warmth and restriction of movement.

2. The work of Poppen was among the first done in the field of G protection in the United States. A Navy Department Bumed Newsletter, Aviation Supplement, Vol. 4 No. 3 dated 2 February 1945[64] describes it as follows: "As early as 1932, studies were undertaken by Captain J. R. Poppen (MC) USN on acceleration effects and protective measures for overcoming G in flight. These studies were first carried on in connection with the Fatigue Laboratory at Harvard, and subsequently at the Naval Aircraft Factory in Philadelphia. Dogs were used in this early work for laboratory purposes. As a result of this investigation a compression belt was developed, the object of which was to provide support to the abdominal area as a means of helping to overcome blood pooling in the splanchnic vessels. The appliance was extensively flight tested, but at this stage of development it was not considered successful." Though complete information is not available, it is believed that the device was a pneumatic belt inflated by a hand pump in advance of an expected episode of increased G. Armstrong and Heim, working at the AAF Materiel Center, Wright Field, in 1938 designed a belt which was inflated by a CO_2 cylinder in a manner similar to that used for inflation of the Mae West life vest.[2]

3. The suit developed by Dr. Frank S. Cotten of Sydney, Australia. One of the first complete pneumodynamic suits developed was the Cotton aerodynamic anti-G suit (CAAG).[4] The writer is not certain of the date on which work began, but design had progressed to such a point in October of 1941 that Doctor Cotton was able to make the following descriptive statement. "The device consists of.-

"1. A series of rubber units applied to the body so as to cover it from the feet to the level of the lower ribs. Each unit consists of a rubber "bag" overlapping its neighbor above and provided with an exit tube for inflation with air. For convenience these units may be fused together in various ways. So far we have combined these as follows:-

"(a) a "sock"

"(b) 4 units running from ankle to top of thigh

"(c) 2 units for the body itself

"It is for future experiment to decide upon the best combination, e.g. whether all units may be fused together, or whether the

optimum may be:-

"(a) a "sock"

"(b) a legging - ankle to below knee

"(c) a pair of "shorts" from below knee to lower ribs.

"2. A device for inflating the rubber units automatically, so as to provide in each the correct pressure for the height of the region above the soles, in the case of any particular G operating during a "loop".

"3. An inextensible outer suit to give support to the inflated rubber bags and to fit the body sufficiently well to avoid excessive ballooning.

"The inflation device consists of a hydrostatic reservoir whose approximate height is equal to the distance between the soles and lower ribs of the seated pilot. This is illustrated in the accompanying diagram.

"The air cells provided must have sufficient space to accommodate the inflow of water during inflation without permitting this water to enter the rubber bags.

"The device worked perfectly on the occasion of its first trial and the following tests, among numerous others, were made.

"1. The subject was exposed to 6.5 G for (28 ±1) seconds with no blackout, no loss of consciousness and no undue discomfort. The most prominent sensation was the feeling that the cheeks were being pulled off.

"2. The subject was exposed to 9.3 G for (19 ±1) seconds with no blackout, loss of consciousness or undue discomfort. Same sensation but in greater degree, of cheeks being pulled down below the jaw. (9.3 G is computed as the mean of 7.5 at the head and 11.3 at the soles exposed to spinning).

"The subject has not been exposed to spinning without the suit for reasons explained to Dr. Kellaway, except for a short time (15") at 4 G when the pain arising from the swelling of the legs became intolerable. Hence 9.3 G with suit is far better tolerated than 4 G without the suit.

"Up to the present this device employed has been built purely with a view of testing the principle of the method so that size has been subordinated to ease of construction. This can readily be developed to a more compact unit certainly not exceeding 20 pounds in weight, and in all probability, reducing finally to something within the limits of 4 to 10 pounds."47

a. The following information from flight tests of the Cotton Suit is extracted from Australian Flying Personnel Research Committee report FR 27 dated December 1942:

"1. In October, 1942, trials, both tactical and operational, of the

suit have been carried out on the Kittyhawk fitted with B.T.H. twin air compressure, high and low pressure reservoirs and accelerometer, by 6 pilots, (5 of them with operational experience). Lone flights were made during which violent aerobatics were performed; and pilots wearing the suit were matched in mock combat against unprotected pilots for one and three-quarters hours. During the tactical trials the pilots using the pneumodynamic suit were able to perform steep turns, pull-outs and spiral dives at from 7.5 to 8.5 G, without discomfort or blacking-out. One pilot reached 10 G without blacking-out, but in the process buckled his tailplane and permanently wrinkled the upper surface of his aircraft. In the mock combats, the unprotected pilot was unable to follow the manoeuvres of his opponents clad in the suit, because of repeated blacking-out.

"While wearing the pneumodynamic suit, therefore, a pilot is limited in his manoevres only by the strength of his aircraft.

"2. All pilots who wore the pneumodynamic suit found that resistance to blacking-out increased and that the fatigue and lassitude commonly experienced after a number of high G manoeuvres was diminished; they finished the trials quite fresh, while the unprotected pilots were markedly fatigued. With the suit, pilots were able to look about and check instruments with ease during high G, without the customary straining and bending of the head to one side. The dragging effects of high G on the cheeks and eyelids remained, also the heaviness of the limbs, but the pilots could at all times control their aircraft without difficulty."[19]

b. A more detailed description of the Cotton suit will be found in FPRC Report No. 407 by Squadron Leader W. K. Stewart.[33]

c. Efforts to simplify the Cotton suit led to the Kelly one-piece suit (K.O.P.)[20]. Models of this were made both with and without pressurization of the feet, and with five and three different pressures. It was noted that use of three pressures was as effective as use of five pressures. This suit was still heavy and complex. No statement of magnitude of air pressures recommended for the CAAF or KOP has been encountered in the available literature.

d. The Cotton Suit was seen by Captain C. A. Maaske in Australia in October 1944. As of that date its weight, bulk, and complexity were still too great to permit general acceptance.

4. The arterial-occlusion suit of Clark and Wood (A.O.S.).

a. In the fall of 1942 while a pneumatic anti-G suit made by Mr. David Clark was being given centrifuge tests at the Mayo Aero Medical Unit, preliminary tests were made at the suggestion of Dr. E. H. Wood on a suit altered so that it consisted of inflatable cuffs around the thighs and arms and an abdominal bladder. This suit was based on the idea that inflation of arm and leg cuffs to pressures high enough to occlude the principal arteries in these regions would cause cessation of blood flow to distal parts, thus limiting the volume of the peripheral vascular bed, increasing blood pressure in the remainder of the body and improving blood flow through the head during increased

positive G. The idea was a departure from those in use up to that time since it removed emphasis from the concept of supporting return of venous blood from the lower parts of the body and placed it on the stopping of blood flow through less critical areas in order to augment flow through more critical ones.

b. This prototype suit, which became known as the Clark-Wood suit or the arterial occlusion suit (A.O.S.) was further refined by Mr. Clark and Dr. Wood. The suit consisted of four pneumatic cuffs, one mounted around each extremity close to the trunk, and an abdominal bladder (Figure 9). Bladders were made of gum rubber on semicircular-shaped forms so that they tended to fit themselves to the underlying parts even when uninflated. Individual groups of bladders consisted of several such cells, lying parallel to one another, each encased in its compartment made of the supporting cloth of the suit. The result is a series of narrow air cells inter-connected but separated by septa, a construction which minimizes the tendency to assume a spheroid shape when inflated. The abdominal bladder group was made in right and left sections which were brought together by slide fasteners in the mid-line in front. Air entered at the left and reached the right side of the suit through tubes which passed across the back. Outward expansion of the bladders was limited by cuffs of inelastic cloth, supported by metal stays, which were fastened taut around the bladder groups and secured by slide fasteners (Figure 9).

c. The suit was inflated to three separate pressures: (1) the thigh cuffs to 4 p.s.i. plus 1 p.s.i. per G, (2) the abdominal bladders to 1 p.s.i. plus 1 p.s.i. per G, and (3) the arm cuffs at a constant pressure of 4 to 4.5 p.s.i. Thus pressures at 6 G were: thighs, 10 p.s.i.; abdominal section, 7 p.s.i.; and arms, 4 p.s.i. (Figure 10).

d. The A.O.S. afforded a high degree of protection against effects of increased positive G. Data from the Mayo Aero Medical Unit indicate an average visual protection of 2.6 G (Table 1).[59] A later model was made without cuffs (Figure 11).

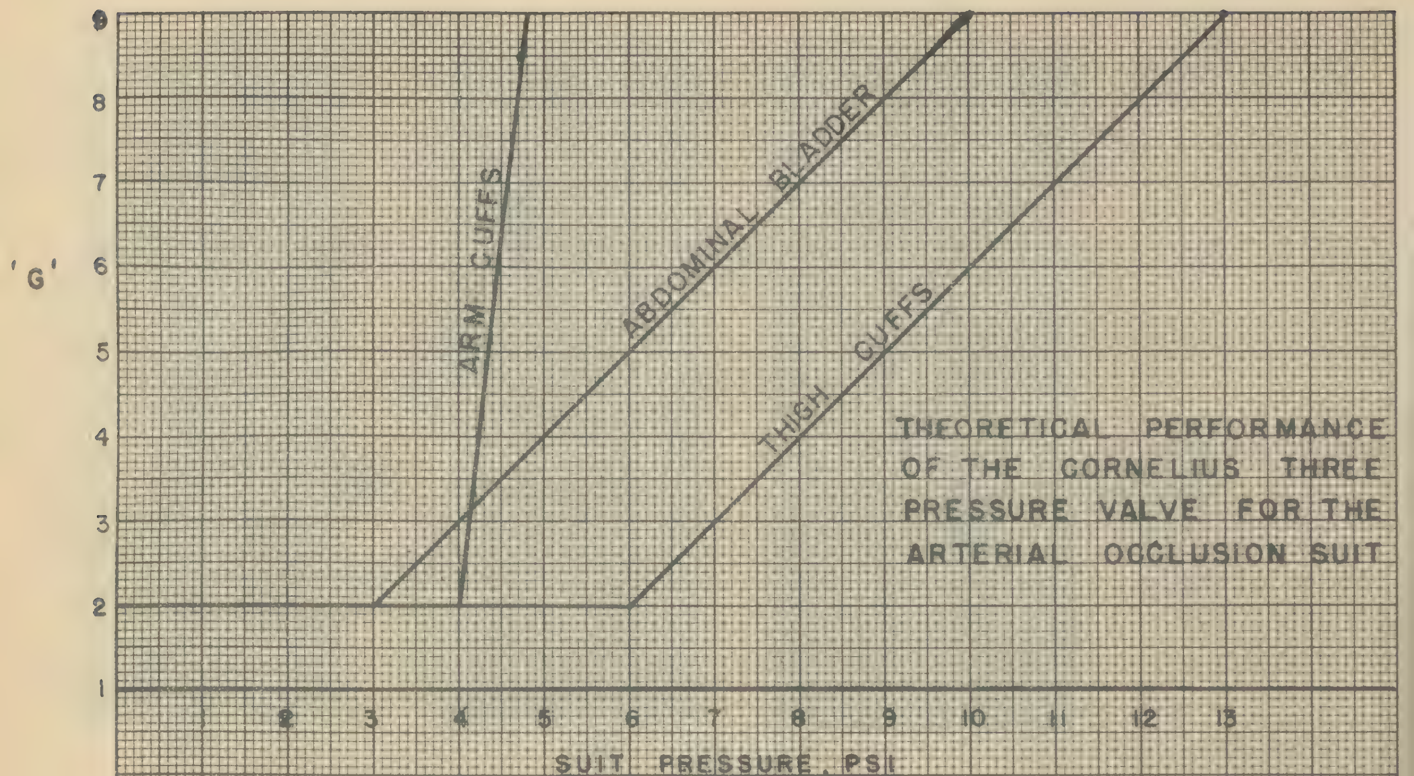
e. The A.O.S. with the G.P.S. was given flight tests at the AAF Proving Ground Command, Eglin Field, in September-October 1943.[67] The G protection offered was found to be adequate, but the suit was rejected because (1) pilots found inflation to the high pressures uncomfortable, and (2) pilots complained that inflation of the arm and thigh cuffs to the arterio-occlusive pressures produced tingling and numbness of the extremities in maneuvers of moderate duration and pain during prolonged exposures to positive G. As a result of these trials the A.O.S. was abandoned as a practical suit for military use. It was a useful tool in the study of effects of pressurizing various parts of the body on G protection.

5. Following up the work of Captain Poppen, the U.S. Navy continued experiments with G suits during the period 1939 to 1941, in association with the Berger Brothers Company, manufacturers of corsets and medical supports, in New Haven, Connecticut. In 1941, Lt. Commander T. J. Ferwerda and Captain L. D. Carson, with the manufacturer, developed a pulsating air pressure suit

MODEL 5 ARTERIAL OCCLUSION SUIT

ENLARGED VIEW OF ABDOMINAL BLADDER SHOWS SEGMENTED CONSTRUCTION

FIGURE 9



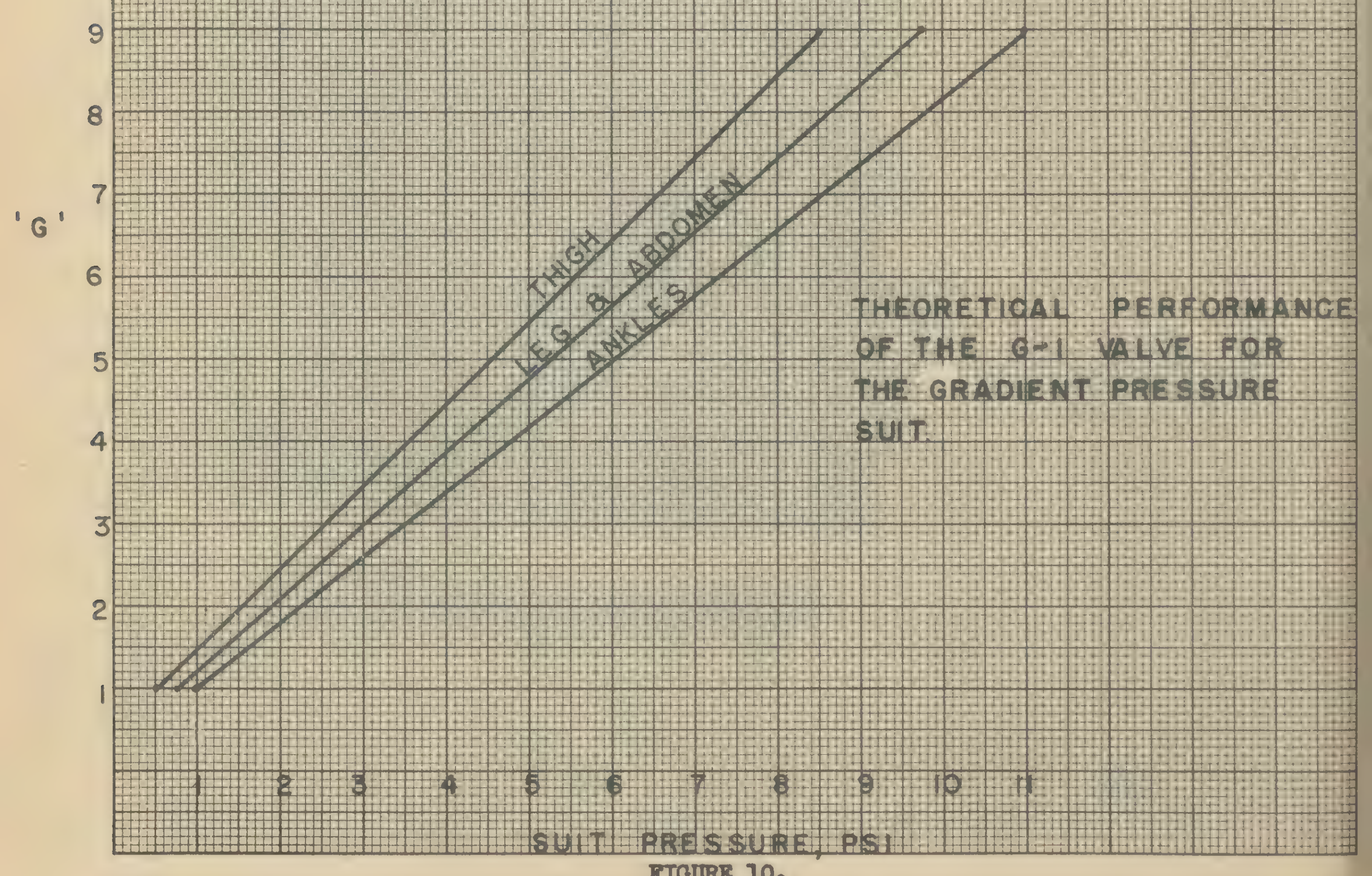


FIGURE 10.

5433
K & E CO., N. Y.
34561

MODEL 9 ARTERIAL OCCLUSION SUIT
FIGURE II.

with a G-activated valve for pressure regulation. One such suit, known to the writer, employed seven separate pressures and pressurized the arms as well as the trunk and legs. Because of the great weight and complexity of the pulsating suit and valve assembly and the fact that it was shown at the RCAF centrifuge and in field trials to give essentially the same protection as a simpler gradient pressure suit (Figure 12), the pulsating suit was abandoned.[64]

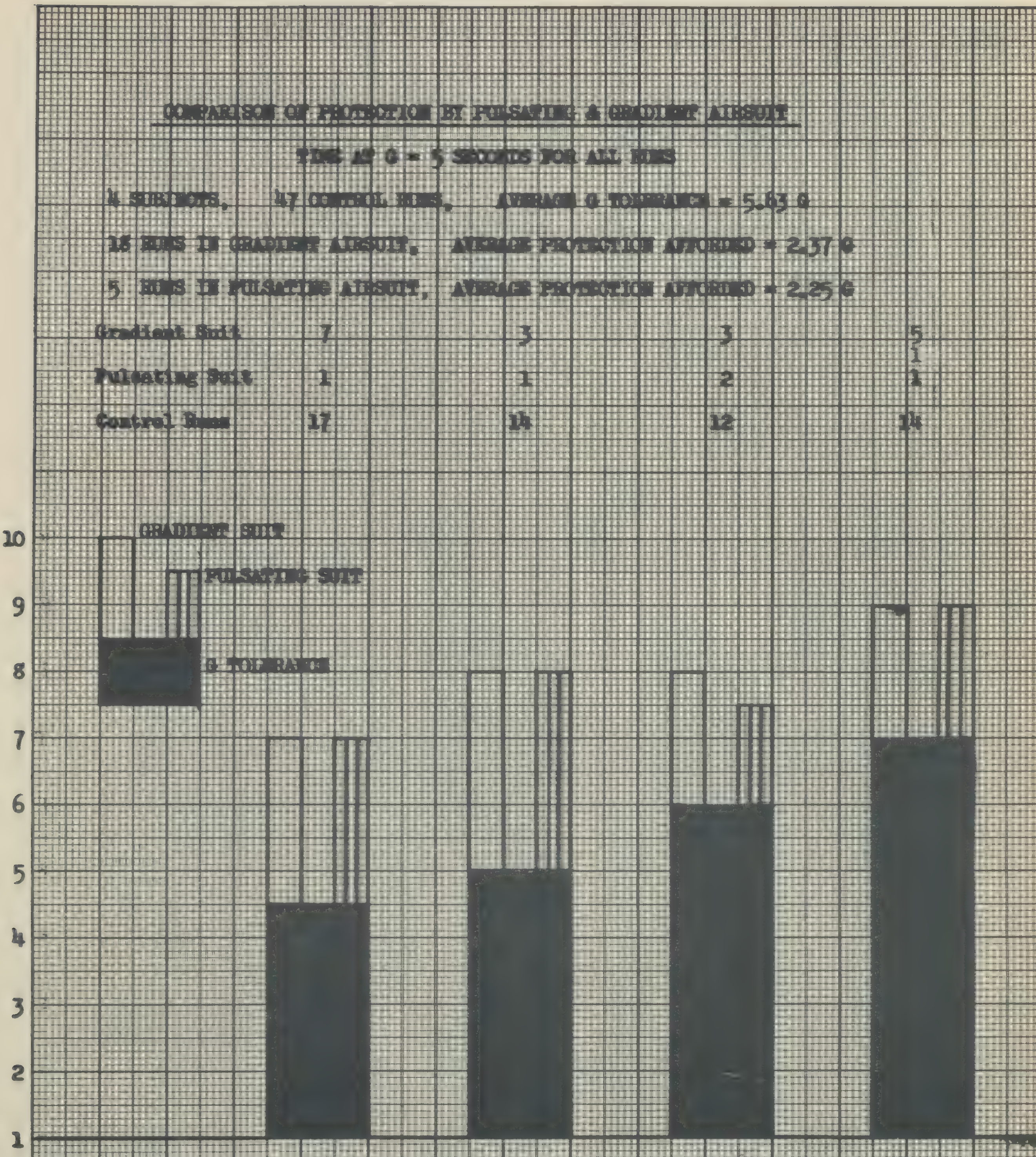
6. The gradient pressure suit (AAF Type G-1).

a. The GPS, like the pulsating suit, was developed by the U. S. Navy with the Berger Brothers Company. This suit is a pair of fitted overalls ensheathing rubber air bladders. Groups of bladders are contained in casings of relatively inelastic lieno weave cloth. Rubber tubing conveys air under pressure to the bladders. Four transversely placed bladders overlie the posterior surface of each calf and four bladders overlie the anterior surface of each thigh. Each of the upper three members of these groups of bladders overlaps the bladder below it. The abdominal bladder, a crown-shaped rubber sac containing internal septa to prevent assumption of a spherical shape during inflation, is incorporated into a corset-like belt stiffened with seven steel stays. Compartments containing the bladders can be opened by slide fasteners to facilitate repair and replacement.

b. Once hung over the shoulders by suspenders, the suit is fastened in place by means of slide fasteners one of which brings together the two sides of the abdominal belt and two of which run the length of the garment, closing it around the legs and thighs (Figure 13). The suit is made in four sizes: large long, large short, small long and small short. Further adjustment is provided by laces placed anteriorly over the legs, posteriorly over the thighs and laterally at the flanks. Straps within the suit can be adjusted to vary leg length and determine the position of the abdominal belt. The weight of this suit is approximately ten pounds.[7]

c. Air pressure is supplied by the positive pressure side of the vacuum instrument pump and is metered to the suit by the G-1 valve, to be described later in this report. Three pressures, high, intermediate, and low are supplied. The high pressure is delivered to the two bladders over the ankle area, the intermediate pressure to the upper two calf bladders and the abdominal bladder, and the low pressure to the four thigh bladders in each leg. Hence the term "gradient pressure suit" is not strictly applicable, since abdominal bladder pressures are higher than thigh bladder pressures. Pressures theoretically delivered by the G-1 valve are shown in Figure 10. Three tubes emerge from the left side of the suit at waist level and terminate in a male disconnect fitting which mates with a female counterpart on the G-1 valve.

d. Average visual protection afforded by the GPS in centrifuge tests at the Mayo[51] and ATSC[7] centrifuges was found to be 1.3 and 1.5 G respectively (Table 1). Variation in protection afforded individual subjects on the ATSC centrifuge is shown in Figure 14. Note that the results obtained in the two laboratories agree closely except for the greater protection against blackout recorded in the tests by ATSC. The fact that the test run employed at the ATSC centrifuge was of 10 seconds duration whereas that at the Mayo Aero



Data from Accelerator Section, No. 1 Clinical Investigation Unit, R.C.A.F.

FIGURE 12.

AAF TYPE G-1 SUIT

FIGURE 13

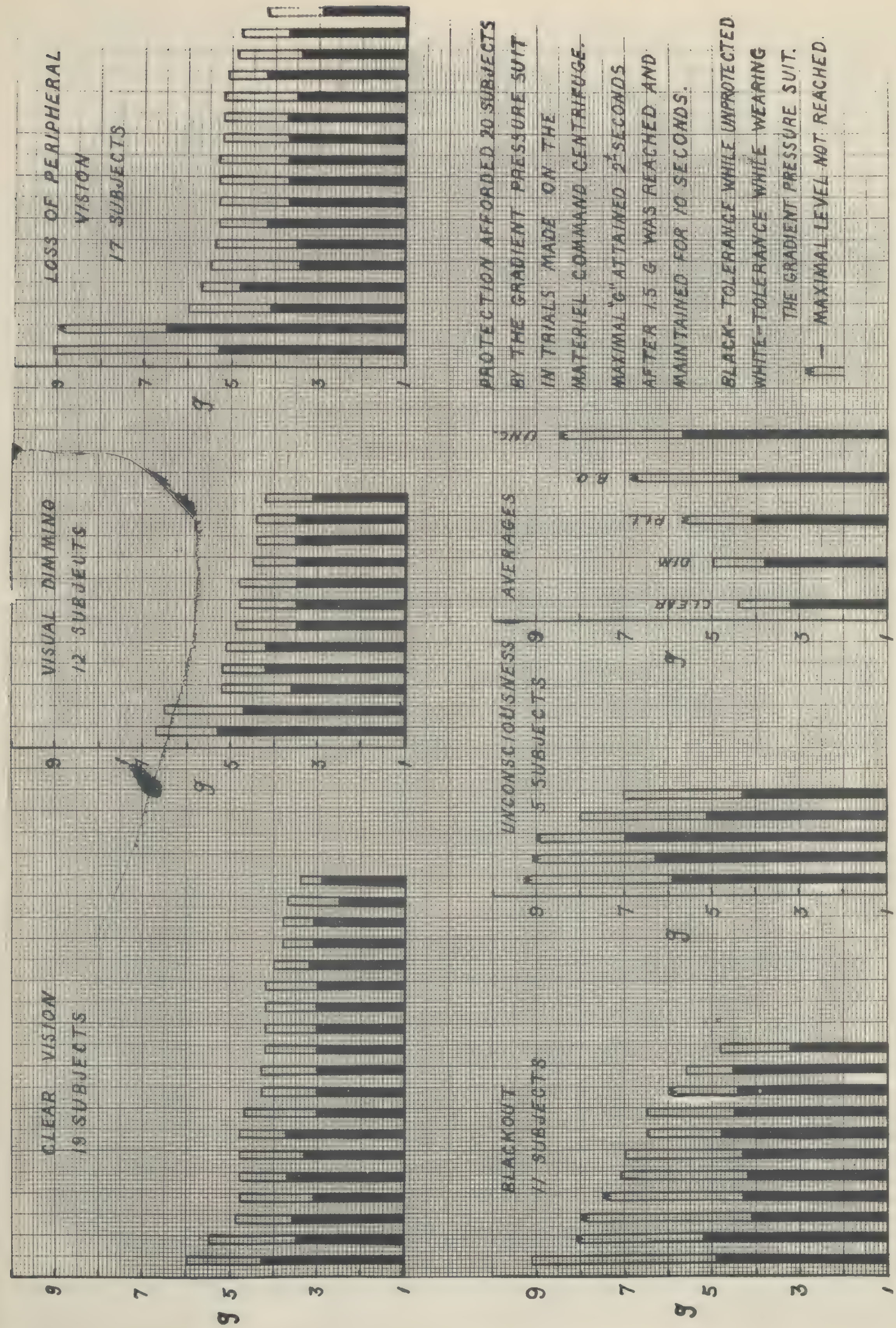

CLEAR VISION
19 SUBJECTS
VISUAL DIMMING
12 SUBJECTS
LOSS OF PERIPHERAL VISION
17 SUBJECTS
BLACKOUT
11 SUBJECTS
UNCONSCIOUSNESS
5 SUBJECTS
AVERAGES
CLEAR
DIM
UNC
PROTECTION AFFORDED 20 SUBJECTS
BY THE GRADIENT PRESSURE SUIT
IN TRIALS MADE ON THE
MATERIEL COMMAND CENTRIFUGE.
MAXIMAL "G" ATTAINED 2± SECONDS
AFTER 7.5 G WAS REACHED AND
MAINTAINED FOR 10 SECONDS.
BLACK- TOLERANCE WHILE UNPROTECTED
WHITE- TOLERANCE WHILE WEARING
THE GRADIENT PRESSURE SUIT.
MAXIMAL LEVEL NOT REACHED.

FIGURE 14

Medical Laboratory was of 15 seconds duration has been advanced as an explanation of this discrepancy on the basis that the suit may have delayed onset of visual symptoms to an extent that 10 seconds were insufficient for blackout to develop at lower G levels when the suit was worn.[51] If this were the cause, the same phenomenon should have been observed in later assays of the G-3 and G-4 suits, since the difference in duration of exposure remained the same. However, this did not occur (Table 1). In the writer's opinion no satisfactory explanation to explain this difference has been advanced to date.

e. Flight tests of the GPS were carried out by the U.S. Navy in November 1942, and some units of the equipment were delivered to combat Navy squadrons in the Spring and Summer of 1943.[64]

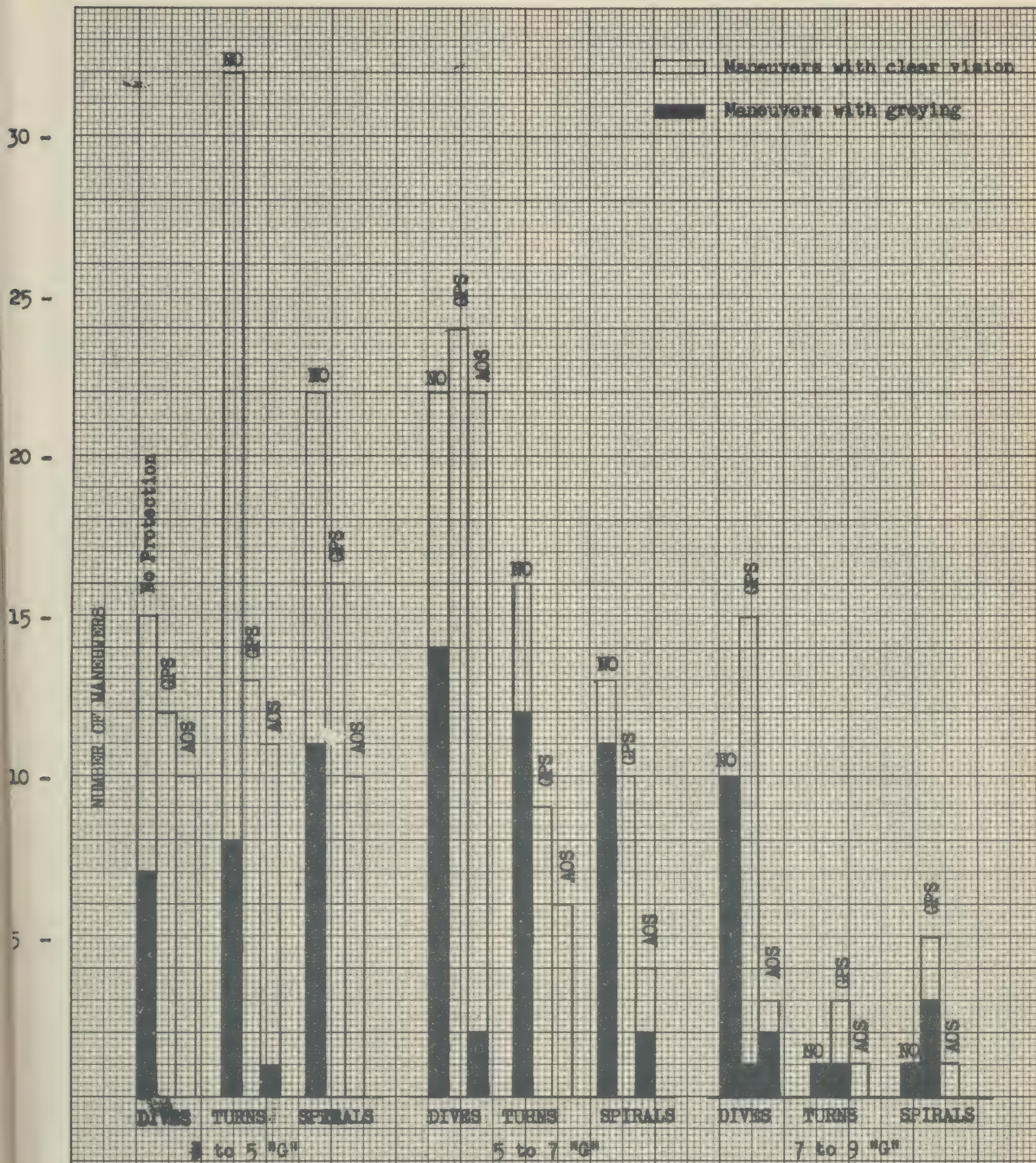
f. Flight service trials of the GPS along with the AOS were carried out by the Army Air Forces at the Proving Ground Command, Eglin Field, Florida, in September-October 1943.[67] Results of these tests confirmed centrifuge data which indicated that the suit protects the wearer against effects of increased positive G. Acceleration data obtained from records made by recording accelerometers in the aircraft and correlated with visual symptoms of the pilots are presented in Figure 15. Whereas some degree of visul impairment occurred in all dive and pullout maneuvers, 180 degree turns, and 360 degree spiral turns in which acceleration reached 7 to 9 G when no suit was worn, visual dimming occurred in only one of 15 dive and pullouts, one of three 180 degree turns, and three of five 360 degree turns at this G level when the GPS was worn.[67] It was concluded by the Proving Ground Command and the AAF Board that the GPS provided adequate G protection, was operationally reliable, and should be given combat trials. Minor changes in the suit were made as a result of these tests. All rubber tubes were made kinkless by spring inserts, a hard rubber air distribution box located in the region of the shoulder blades was removed, the knee dimensions were enlarged, a test kit for the valve was devised, and the valve was made to begin suit pressurization at 2.5 instead of 1.5 G.

g. Twenty-two GPS units were taken to the Eighth and Ninth Air Force in the ETO in December 1943 by Captain G. L. Maison.[18] When the results of non-operational tests were complete the Eighth Air Force ordered 1000 units for combat use. Five hundred were delivered before the G-1 assembly was replaced by the simpler G-2 suit and valve.

h. Thus centrifuge and field trials of the G-1 suit established the fact that anti-G suits which offered a protection of 1 to 1.5 G on the centrifuge would be adequate in contemporary aircraft began the trend toward lower suit pressures than those employed in the AOS, and served to introduce G suits into Army and Navy combat units. Yet the suit had many defects. It was heavy (ten pounds), hot, restricted movement too much, and it, with its complicated valve and oil separator, imposed more weight penalty on the aircraft than was desirable. It was obvious to both services that simplification was necessary.

7. The AAF type G-2 suit (single pressure suit).

a. Centrifuge studies with the G-1 suit produced evidence that the three pressure system was an unnecessary encumbrance. Lamport *et al*



Incidence of visual disturbances in "g" maneuvers without protection and with protection of the gradient pressure suit (Berger) and the arterial occlusion suit (Clark Wood).

FIGURE 15.

From AAFPGC Rpt. No. 7-43-9 dtd 4 Nov. 1943

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working at the Mayo centrifuge noted that the protection offered by a type G-1 suit remained the same whether it was (a) inflated with the standard gradient pressure arrangement, (b) used with a constant pressure in the abdominal bladder and gradient pressures in the leg bladders, (c) used with a single pressure, increasing with the G, in the leg bladders and a constant pressure in the abdominal bladder.[52] The Wright Field group noted that the pressures actually delivered by the three pressure G-1 valve were essentially the same and considered trial of a single pressure system the next step in simplification of the G-1 suit.[7] The Berger Brothers Company was requested to make such a suit, and the result became the AAF type G-2.

b. The G-2 suit is similar to the G-1 suit in its general outward appearance, sizing, lacing adjustment, and method of donning (Figure 16). The bladder system in the legs differs from that in the G-1 suit in that there are long rectangular bladders lying lengthwise, one over each thigh and one over each calf (Figure 17). The abdominal bladder is the same as that of the G-1 suit, but the abdominal belt was simplified by making it a part of the outer garment rather than a separate unit. All bladders are inflated to the same pressure. Thus the number of bladders was reduced from 17 to 5 and much rubber tubing was eliminated. These changes simplified the suit and valve, and reduced the weight of the suit to 4-1/2 pounds.

c. The protection offered by the G-2 suit on the centrifuge was determined on the Mayo and ATSC centrifuges. At the Mayo centrifuge with suit pressures of 1.25 p.s.i. per G average visual protection was 1.4 G (Table 1).[51] At the ATSC centrifuge, with suit pressures of 1 p.s.i. per G, average visual protection was also 1.4 G (Table 1).[13] Variation in protection afforded invividual subjects is shown in Figure 18. These values compare closely with centrifuge protection obtained with use of the G-1 suit, validating the concept that a single pressure suit with no attention given to inflation from below upward and no attention to the idea of gradient pressure can provide G protection of 1 to 2 G.

d. The G-2 suit was given service trials at Eglin Field in February 1944, and approved to replace the G-1 suit by the AAF Proving Ground Command[68] and subsequently by the AAF Board.[69] Protection in the aircraft, from observations in which the duration of acceleration was not taken into consideration, was similar to that noted with the G-1 (Figure 19).

e. Thirty-five hundred G-2 suits were sent to the Eighth and Ninth Air Forces and saw use over Europe.

f. The G-2 suit, though an improvement over type G-1, remained more bulky and heavy than was desirable. Further attention to simplicity, coolness, and lighter weight was clearly necessary.

8. Early Clark suits with single piece nylon bladder systems. In January 1944 David Clark of the David Clark Company, Worcester, Massachusetts, with Dr. E. H. Wood of the Mayo Aero Medical Laboratory, introduced the use of a single piece bladder system made of vinylite coated nylon cloth to replace the older system of five separate bladders of rubber or synthetic rubber joined by rubber tubing (Figures 17 and 20). With this single piece system the five air cells to cover abdomen, thighs, and calfs are formed by stitching the nylon

AAF TYPE G-2 SUIT
SINGLE PRESSURE SYSTEM

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FIGURE 16

A. GUM RUBBER TYPE WITH SEPARATE CONNECTED BLADDERS (BERGER BROS'. AAF TYPES G-2 AND G-3)

B. SINGLE PIECE VINYLITE COATED NYLON BLADDER SYSTEM (DAVID CLARK CO.'S NYLON BLADDER SUIT, AAF TYPE G-3, NAVY Z-1 AND Z-2).

SINGLE PRESSURE BLADDER SYSTEM FOR G-SUITS

FIGURE 17

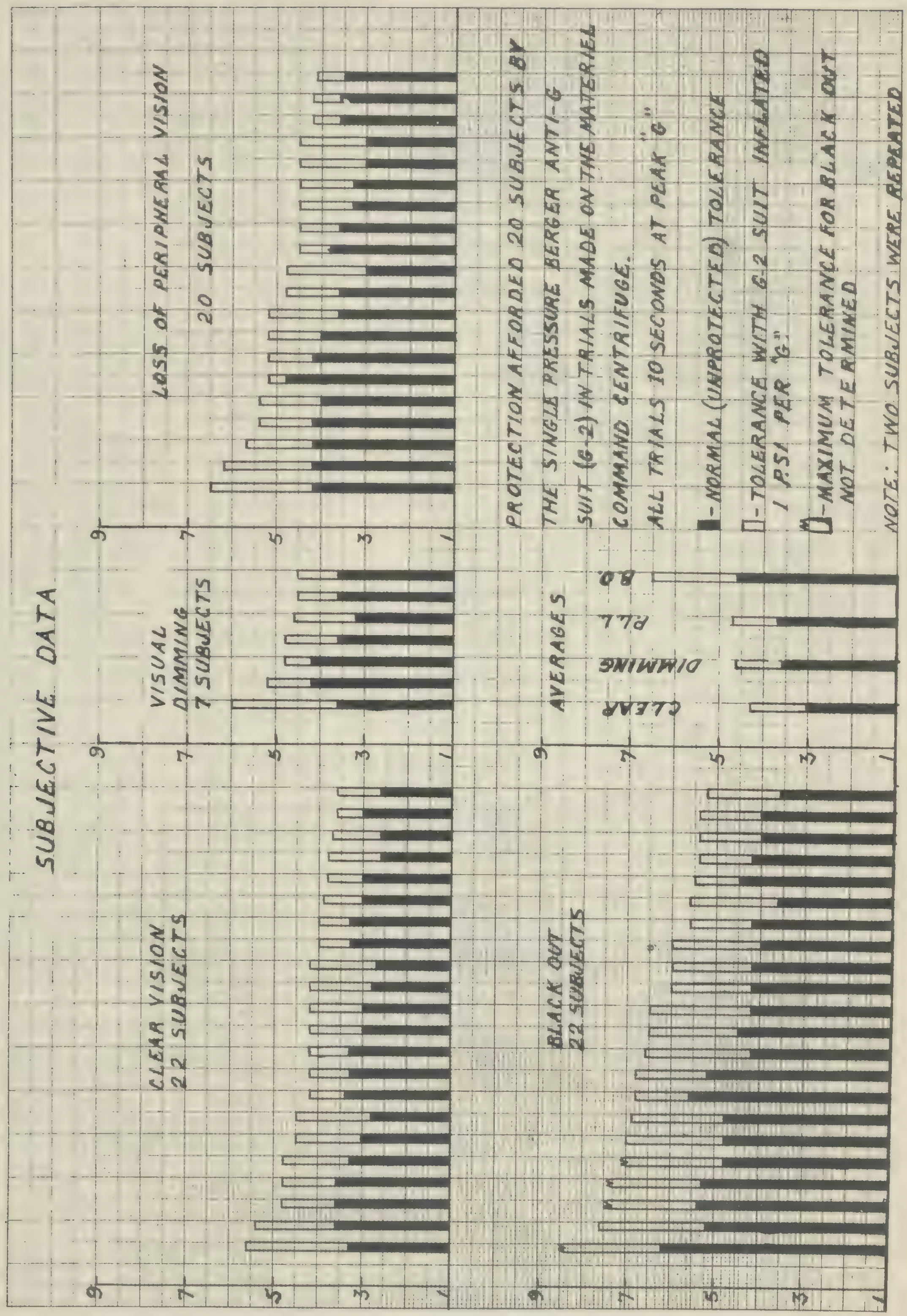
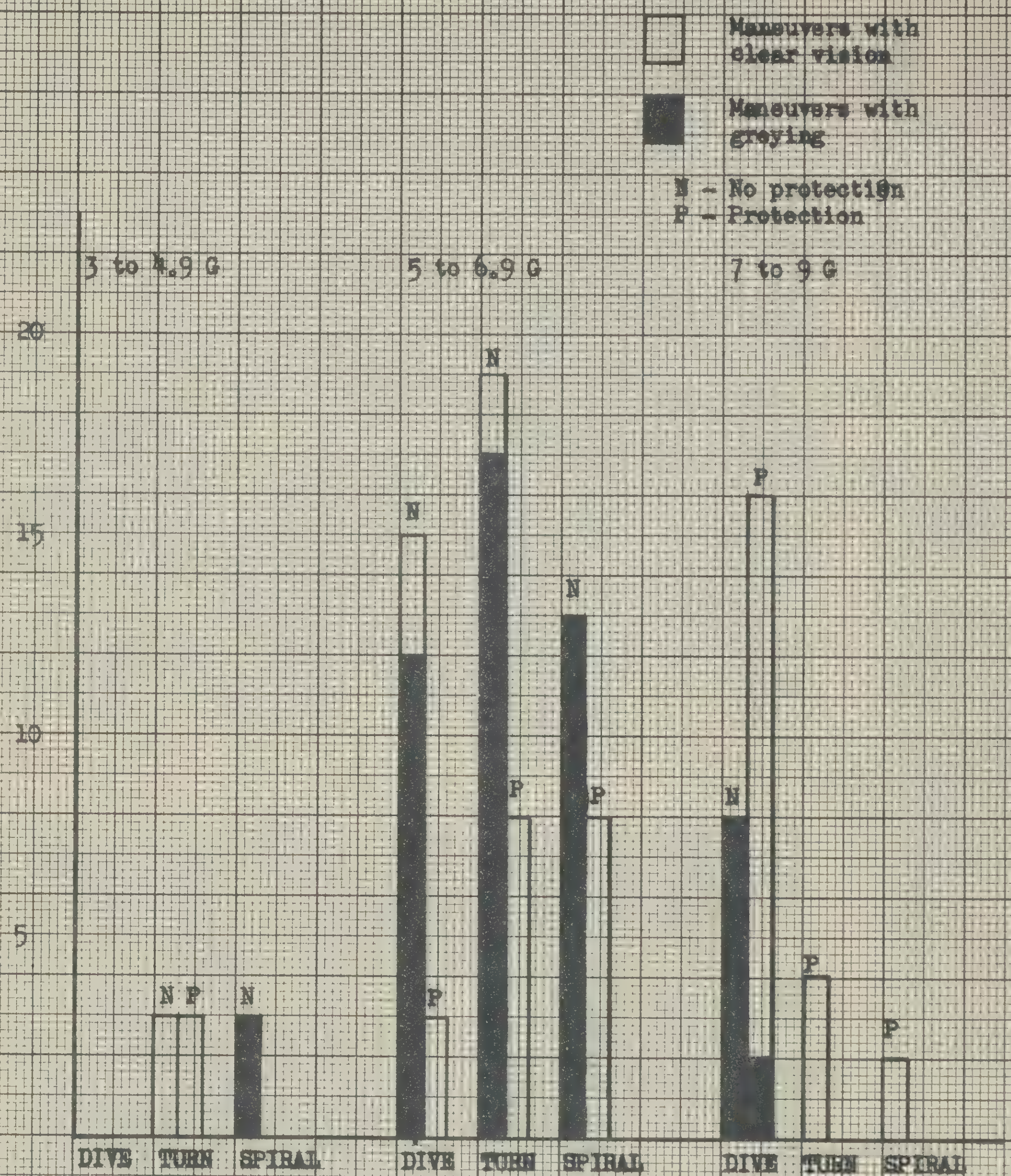

SUBJECTIVE DATA
CLEAR VISION
22 SUBJECTS
VISUAL
DIMMING
7 SUBJECTS
LOSS OF PERIPHERAL VISION
20 SUBJECTS
BLACK OUT
22 SUBJECTS
AVERAGES
CLEAR
DIMMING
PLL
BO
PROTECTION AFFORDED 20 SUBJECTS BY
THE SINGLE PRESSURE BERGER ANTI-G
SUIT (G-2) IN TRIALS MADE ON THE MATERIEL
COMMAND CENTRIFUGE.
ALL TRIALS 10 SECONDS AT PEAK "G"
-NORMAL (UNPROTECTED) TOLERANCE
-TOLERANCE WITH G-2 SUIT INFLATED
1 PSI PER "G"
-MAXIMUM TOLERANCE FOR BLACK OUT
NOT DETERMINED
NOTE: TWO SUBJECTS WERE REPEATED
1
3
5
7
9
G
G

FIGURE 18



Incidence of visual disturbance in "g" maneuvers without protection and with protection. (G-2 suit)

From AAFPGC Report No. 7-44-6 dated 29 April 1944

FIGURE 19.

A. RELATIONSHIP OF BLADDERS TO CLARK NYLON BLADDER SUIT. MODEL 21.

B. BLADDER SYSTEM INFLATED

SINGLE PRESSURE NYLON BLADDER SYSTEM

FIGURE 20

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cloth which has been cut to the proper pattern and sealing the seams with vinylite cement. Kinking of the connecting channels between bladders at the flexures of the body and of the tube which leads from the suit is prevented by a coiled steel spring insert placed within the bladder system. The vinylite coated nylon bladder unit was ensheathed in a close fitting envelope of oxford nylon cloth which gave support to the seams of the bladder during inflation. Development of the single piece bladder system with spring inserts proved to be an important advance in the construction of G suits and has since been adopted for all G suits in use at the present time by the Army Air Forces and the U.S. Navy, whether the bladders are made of coated cloth or of rubber substitutes.

a. Twelve initial models of the single piece nylon bladder system, single pressure suit were made. Model 21, typical of this group, is shown in Figure 21. All provided full coverage from the level of the lower ribs to the ankles and all had essentially the same sized bladders. They differed in the manner of sizing adjustment, the method of keeping airlines open, the method of opening the abdominal section, etc. Average visual protection as measured in centrifuge tests at the Mayo Aero Medical Unit was 1.9 G (Lambert, E. H., Minutes of the Sixth Meeting of the Subcommittee on Acceleration, June 1944).

b. This type of Clark nylon bladder suit is the lineal antecedent of the coverall type of suit used at present by the U.S. Navy. For military use the abdominal bladder was made smaller to promote comfort during inflation, and the resultant decrease in protection was accepted.

9. The AAF Types G-3 and G-3A suits (skeleton suit, cutaway suit).

a. In the spring of 1944 the most pressing need in G suit development continued to be one for simplification, lighter weight, and coolness. The Mayo group had pointed out that the simple single unit pneumatic bladder system first made by Clark, if incorporated into any supporting garment which would provide reasonable fit and was relatively inelastic, could be expected to provide adequate G-protection.[61] The trend toward greater simplification received much needed impetus when Lt. Commander Harry Schroeder, on returning from a trip to the Pacific theatre of operations, recommended development of two garments for trial, one a skeleton suit consisting only of the supporting elements required by the bladder system and the other a coverall patterned after the standard summer flying suit. The first was to be designed for use with other clothing, the second to be used alone as a flying suit. This plan ultimately led to two types of suits which have been called by the Army types G-3 and G-4 respectively.

b. The type G-3 suit is a wrap-around garment, waist to ankle in length, which pressurizes the same areas of the body as the G-2 suit but covers only those regions of the body which are actually pressurized: abdomen, thighs, and calves. The crotch and the anterior and posterior knee regions are cut away. Two models of the G-3 suit were produced, one by the Berger Brothers Company (Figure 22), the other by the David Clark Company (Figure 23). The Berger G-3 model had the following characteristics:

MODEL 21 CLARK NYLON BLADDER SUIT

FIGURE 21

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G-3 SUIT

(BERGER BROS. MODEL)

NOTE TUBE ACROSS BACK

FIGURE 22

G-3 SUIT
(DAVID CLARK CO. MODEL)
NOTE ABSENCE OF TUBE ACROSS BACK
FIGURE 23

(1) The bladder system was the same as that in the G-2 suit, and consisted of five separate rubber bladders joined by tubing (Figure 17).

(2) The abdominal belt section was separate from the outer fabric of the suit and was closed by a slide fastener within that which finally closed the outer garment.

(3) Air entered the suit by a tube attached to the left side of the abdominal section. Air reached the right leg by passing through a tube which coursed across the back of the garment, lying in the region of the lumbar curvature of the spine. This is unacceptable, since the tube constitutes a pressure point which produces discomfort with prolonged usage.

c. The Clark G-3 model differed from the Berger type in the following respects:

(1) The bladder system was of the single piece vinylite coated nylon type with a spring insert described in paragraph 8 (Figure 17).

(2) The abdominal bladder was an integral part of the anterior belt section, so that one slide fastener, located on the right side of the belt section, sufficed to close the suits around the trunk.

(3) No tubing or spring insert crossed the back of the suit. Air reached the right leg by passing through the abdominal air cell, a feature made possible by the fact that the belt section slide fastener was located at the side rather than in the front.[14]

d. Forty-one hundred type G-3 suits were delivered to the Eighth, Ninth and Twelfth Air Forces in the ETO and MTO during 1944.

e. In November 1944 the G suit was officially standardized by the AAF by authority of Assistant Chief of Air Staff, Materiel and Services (Teletype AFDBS-4-A6481 dated 23 November) and issue on the basis of one suit for each fighter pilot in the AAF was established. The choice of suit to be procured in quantity lay between the G-3 skeleton type and the G-4 coverall type to be described in a later section. All previous experience in the Eighth and Ninth Air Forces had shown that Army pilots preferred to fly combat missions in standard uniforms so that in event of being forced down in enemy territory they would both be easily recognizable as an officer in the USAAF and be wearing clothing which would be adequate and comfortable during long periods of imprisonment. Even the G-1 and G-2 suits, when used in combat, were usually worn as an adjunct over standard clothing. Largely because of this fact, the skeleton suit, which was designed for use with other clothing, was selected for routine AAF use.

f. The suit finally evolved for production purposes differed in details from earlier G-3 suits and was designated AAF type G-3A (Figure 24). At the present writing it is the suit used by the AAF. Essentially the G-3A suit is a modification of the Clark G-3 suit, in that it utilizes the single piece bladder system with spring insert, has no tubing across the back, and

TYPE G-3-A SUIT

FIGURE 24

carries the slide fastener which closes the abdominal belt section on the right side. The following details of construction of the G-3A suit may be noted:

(1) Previous experience with fabrics for use in G suits had indicated that the cloth should withstand tearing forces of 125 pounds on the warp and fill. Use of airplane cloth in a few instances had resulted in some tearing of the outer cloth in ordinary usage. Oxford weave nylon cloth conforming to AAF Specification No. 16169 and basket weave nylon cloth conforming to AAF Specification No. 16189 are satisfactory. In the G-3A suit, the basket weave nylon cloth is used to form the outer garment, whereas the oxford weave cloth, chosen because it has less tendency for slippage at the seams, is used for the envelope immediately surrounding the bladder system.

(2) Slide fasteners for the legs and abdominal section are of the Talon type 1A. This fastener, slightly larger and heavier than the Talon type previously used in G-3 suits, was chosen because it is easier to engage and being stronger can be expected to result in fewer maintenance problems.

(3) Like the G-1, G-2 and G-3 suits, the G-3A suit is made in four sizes: large long, large short, small long, small short. Laces over the calves, thighs and flanks provide further adjustment of size.

(4) The single piece bladder system is made of neoprene and encased in a close fitting bladder envelope of oxford weave nylon. Tabs from the bladders protrude through slits in the bladder envelope. When the bladder in its envelope is placed inside the outer casing of the suit, these grippers mate with counterparts in the casing to fasten the bladder system in place. Thus the bladder system of the G-3A suit can be removed for repair or replacement. The complete G-3A suit weighs 3-1/4 pounds. This figure is to be compared with 2.75 pounds for the Berger G-3 suit and 2.25 pounds for the Clark G-3 suit. The G-3A suit has been manufactured by the Berger Brothers Company and by Munsingwear, Inc.

g. Centrifuge tests at the Aero Medical Laboratory, Engineering Division, ATSC, where the G-3 suit was pressurized at 1.0 p.s.i./G on a scale which assumes pressure rise to begin at 0 G indicated that the average visual protection was 1.1 G.[14] The corresponding figure from the Mayo Aero Medical Laboratory was 1.2 G (Table 1)(personal communication from E. H. Wood). Individual variation in protection is shown in Figure 25.

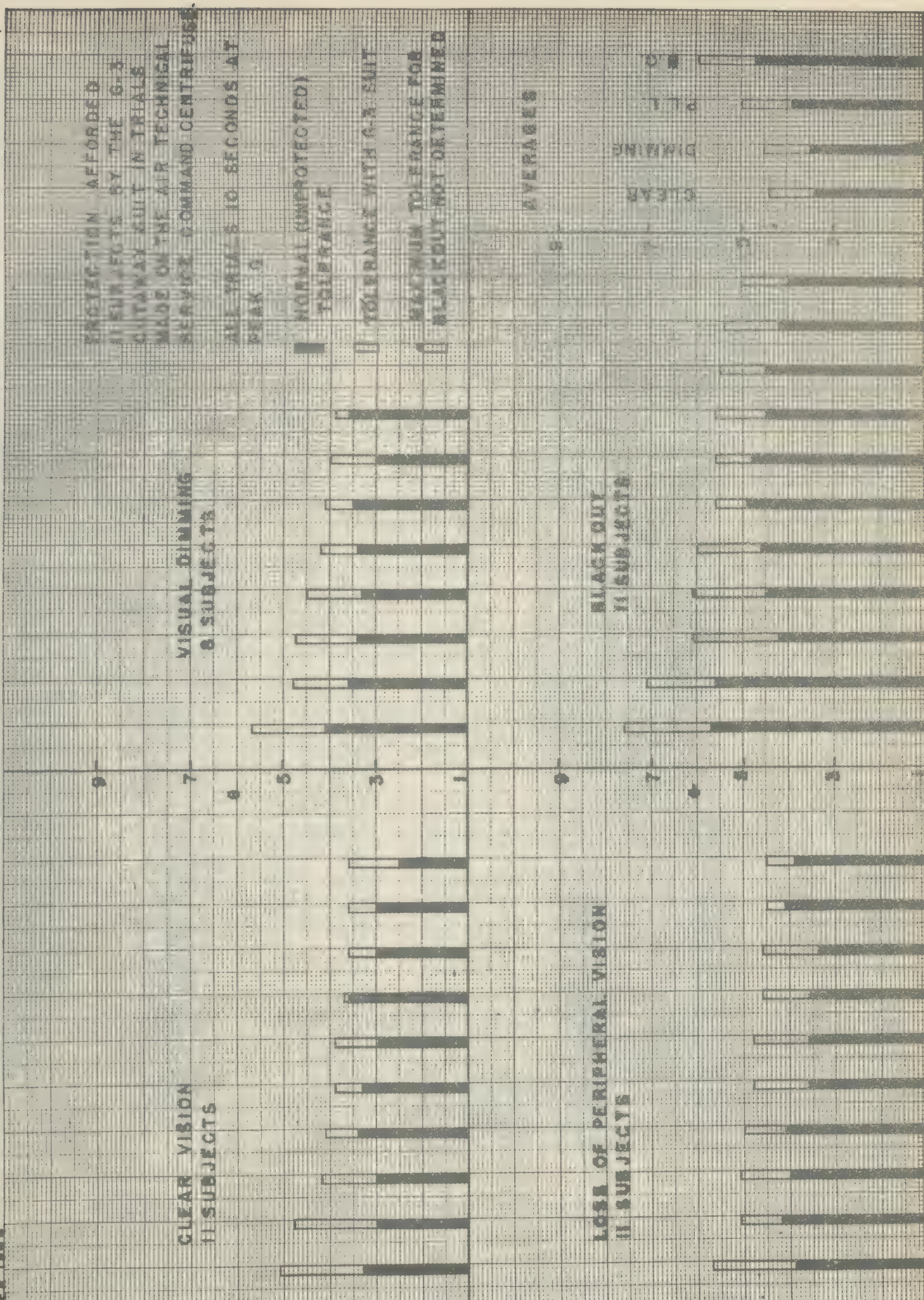
h. Observations made in the Twelfth Air Force in the MTO established the fact that the G-3 suit gives adequate protection in the aircraft.[9]

10. The U.S. Navy Z-1 and Z-2 suits (AAF type G-4, coverall suit).

a. The U.S. Navy chose the coverall type G suit as most applicable to its needs and standardized a model made by the David Clark Company as type Z-1. A later model with a few changes became model Z-2. These suits are patterned after the summer coverall flying suit and provide full coverages of arms, trunk, and legs (Figure 26). Into the abdominal and leg sections are built a single piece vinylite coated nylon bladder system of the type used in

ENGINEERING DIVISION,
MEMORANDUM REPORT NO. TSEAL 3-696-51F,
16 NOVEMBER 1944

APPENDIX 3 (CONT.)
FIGURE VII



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MX-389
-18-

Y-91422

3269

FIGURE 25

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NAVY Z-1 (AAF G-4) COVERALL SUIT

FIGURE 26

Clark G-3 suits (Figure 17). The legs, which must fit more closely than those of an ordinary flying suit, are opened by slide fasteners when the suit is donned. If the slide fastener which opens the upper part of the suit were to be located in the mid-line in front, as is the case with ordinary flying suits, the abdominal bladder would either have to be divided or allowed to hang free in the abdominal section of the suit. These complications are avoided by placing the slide fastener diagonally from a point over the right hip to the center of the garment at the neck. Thus the abdominal bladder is incorporated into the front of the suit and lies to the left of the slide fastener which closes the trunk section. Model Z-1 was made to fit tightly at the ankles. Model Z-2 has false outer legs which surround the ankles loosely, giving more the appearance of a summer flying suit. For reasons of appearance and simplicity, no lacing adjustments are provided.

b. As a result the suit is furnished in nine sizes as follows:

Size 34	medium waist	25" - 27"
36	short waist	27" - 29"
36	long waist	27" - 29"
38	short waist	30" - 32"
38	long waist	30" - 32"
40	short waist	33" - 35"
40	long waist	33" - 35"
42	medium waist	36" - 38"
44	medium waist	39" - 41"

c. Model Z-2 is further provided with slide fastener insets which can be used where needed to increase leg circumference while preserving small abdominal girth. The Z-2 suit weighs 3-1/4 pounds.

d. Protection offered by the Z-series of suits (AAF G-4) lies in the range of 1 to 1.5 G. Figures for average visual protection are: ATSC centrifuge[14] (0.86 p.s.i./G, pressure assumed to start at 0 G) 1.0 G; Mayo Aero Medical Laboratory[63] (1.0 p.s.i./G, pressure assumed from 1.5 G) 1.1 G; USC Aero Medical Laboratory[42] (1.0 p.s.i./G, pressure assumed from 1.75 G) 1.3 G and 1.2 G for Z-1 and Z-2. (Table 1). Individual variation in protection is shown in Figure 27.

e. Experience of the U.S. Navy has amply established the protective value of the Z series suit in the aircraft.

11. The pneumatic lever suit.

a. The pneumatic lever suit (PLS) was developed by Dr. Harold Lamport and his colleagues at the John B. Pierce Foundation, Yale University, in conjunction with the Pioneer Products Division of the General Electric Company. It differs from the other pneumodynamic anti-G suits herein described in that the air cells, instead of being contained in the fabric which covers the parts of the body to be pressurized, are contained in separate envelopes which lie next to these parts. Inflation of these bladders applies no direct pressure to the body, but pressurizes the contiguous part by tightening

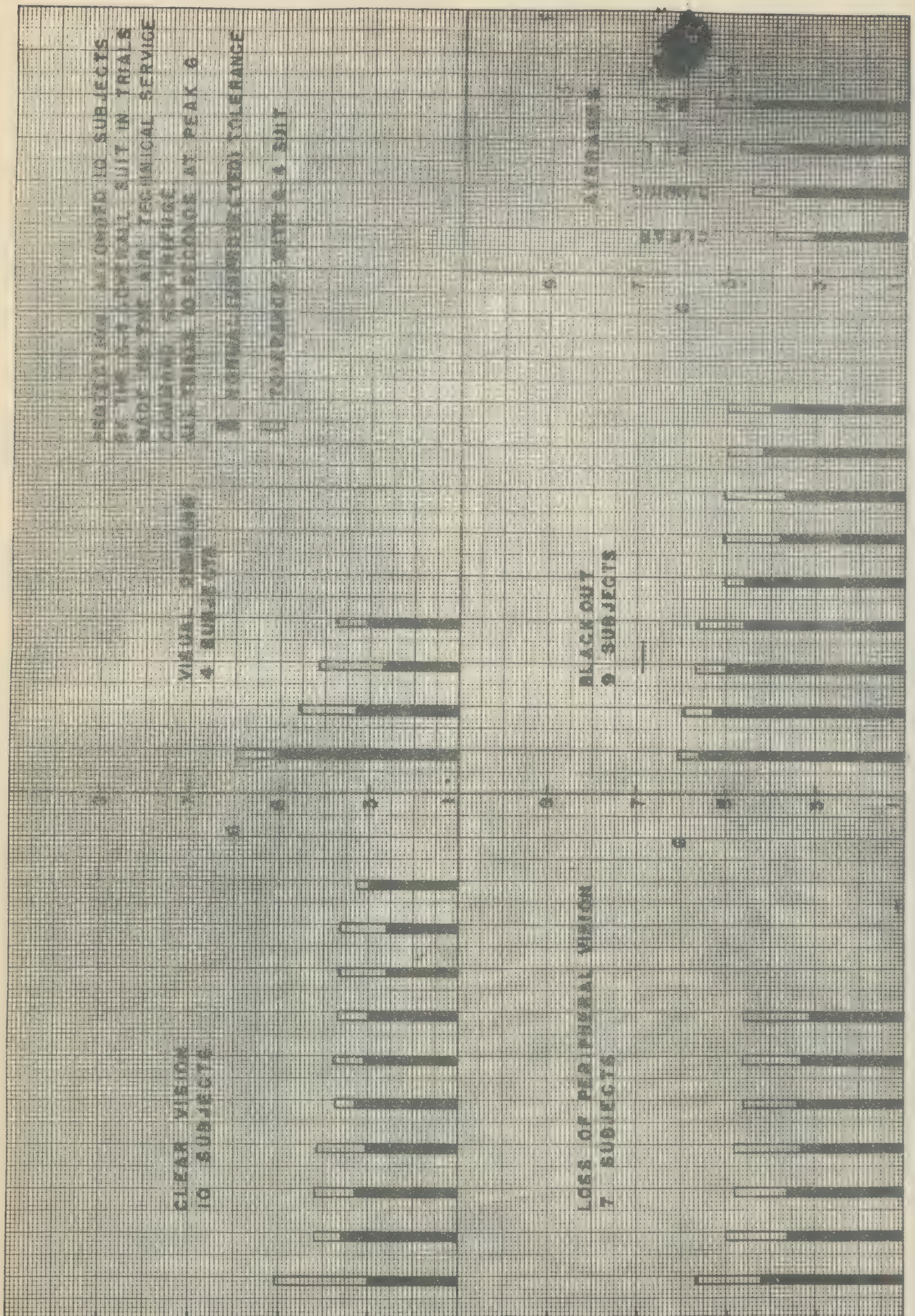
CLEAR VISION
10 SUBJECTS
4 SUBJECTS
LOSS OF PERIPHERAL VISION
7 SUBJECTS
BLACK OUT
9 SUBJECTS
AVERAGES
G
1
3
5
7
9

FIGURE 27

the suit fabric surrounding that part. This tightening is accomplished by use of interlocking tapes which connect the bladder envelopes to the main part of the suit. During inflation of the bladders, tension in these tapes is transmitted to the main suit by the capstan principle, causing it to be tightened around the body (Figure 28).

b. Early models employed the pneumatic lever system for leg pressurization and used the abdominal bladder developed for the G-1 and G-2 suits. Tested by Lamport on the ATSC centrifuge, this suit was found to give an average visual protection of 1.2 G (Table 1).[54]

c. The latest model, model L-12, has been greatly refined. Patterned after a summer flying suit, it has the outward appearance of the G-4 coverall suit. The pneumatic lever principle has been applied to the abdomen as well as the legs (Figure 28). When the suit is worn for use, the underlying pneumatic lever system is covered by the outer fabric of the suit. Centrifuge test at the U.S.C. Aero Medical Laboratory indicate that this suit when inflated at a rate of 2.2 p.s.i. per G beginning at 2.0 p.s.i. at 2 G offered an average visual protection of 1.6 G.[56] Thus the protection offered by Model L-12 PLS with these pressures is slightly higher than that offered by the G-3 and Z-2 types of suits currently used by the AAF and NAF.

d. Advantages claimed for the pneumatic lever suit include:

(1) Better cooling from the increased ventilation achieved by having no airtight bladders overlying bodily parts.

(2) Increased comfort during pressurization of the suit. Lamport, Clark, and Herrington[56] compared the opinions of 12 subjects who wore the Z-1 and Model L-12 PLS in centrifuge tests. Protection afforded this group of subjects by the two suits was essentially the same. Eight of the 12 subjects considered the PLS the more comfortable of the two suits. Ten subjects preferred pressurization of the abdomen by the pneumatic lever method. Four preferred pressurization of the legs by the G-4 suit, One preferred the pneumatic lever method. The others found them equal.

e. The chief disadvantage of the PLS has been the fact that it requires pressurization to higher pressures than other types of G suits in order that comparable G protection be achieved. A pressure of 2.2 p.s.i. per G is recommended for model L-12,[56] a figure to be compared with 1± p.s.i. per G in other suits currently in use. The vacuum instrument pump, the standard source of pressure for anti-G suits in conventional fighter aircraft, is barely adequate to supply this lower pressure rapidly at higher altitudes (see below) and would be inadequate to pressurize the PLS at these altitudes unless the suit were effective at pressures lower than 2.2 p.s.i. per G.

f. The PLS is now considered by its designers as ready for service trials.[56] As of this date it has not been tested by the AAF. Suits are on order by the AAF, and tests will be carried out.

g. The principle employed by the PLS to apply pressure to the body has been used by Henry and his associates in a flexible light weight pressure suit for use at very high altitudes.

JNINFLATED

INFLATEC

DETAIL OF ~~INFLATED~~ ABDOMINAL CAPSTAN, NOTE "PIANO HINGE" LACING.

PNEUMATIC LEVER SUIT MODEL L 12.

FIGURE 28

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12. Canadian and RAF pneumatic suits. During 1945 pneumatic anti-G suits were developed both at the RCAF Acceleration Laboratory at Toronto and at the RAF laboratory at Farnsborough. The Canadian suits are similar in principle to the G-3 and Z-1 suits described above. Single piece bladder systems are made of rubber coated fabric and contain spring inserts to prevent kinking at the flexures of the body. One model has been made which provides full coverage from waist to ankles (Figure 29) and another cutaway version is similar to AAF type G-3 (Figure 30). The RAF model, also made in full coverage and skeleton styles (Figures 31 and 32), differs from other G suits in that right and left halves of the bladder system are not connected. The slide fastener opening the abdominal belt section lies in the mid-line in front, bisecting the abdominal bladder. Two inlet tubes, one on each side of the suit, are provided to serve the left and right halves of the bladder system. Data on protection offered subjects wearing these suits in centrifuge tests are not available to the writer at present. From the design of the suits in comparison with other G suits one would predict an average visual protection in the range of 1.0 to 1.5 G if the suits were pressurized at 1 p.s.i. per G. The RAF pneumatic suit has been given flight tests by Davidson and is reported to possess pilot acceptability.[31]

CANADIAN PNEUMATIC SUIT

FIGURE 29

CUTAWAY VERSION OF CANADIAN PNEUMATIC SUIT

FIGURE 30

RAF PNEUMATIC ANTI G SUIT
COMPLETE COVERAGE FROM CHEST TO ANKLES
FOR BLADDER DESIGN, SEE FIGURE 32.

FIGURE 31

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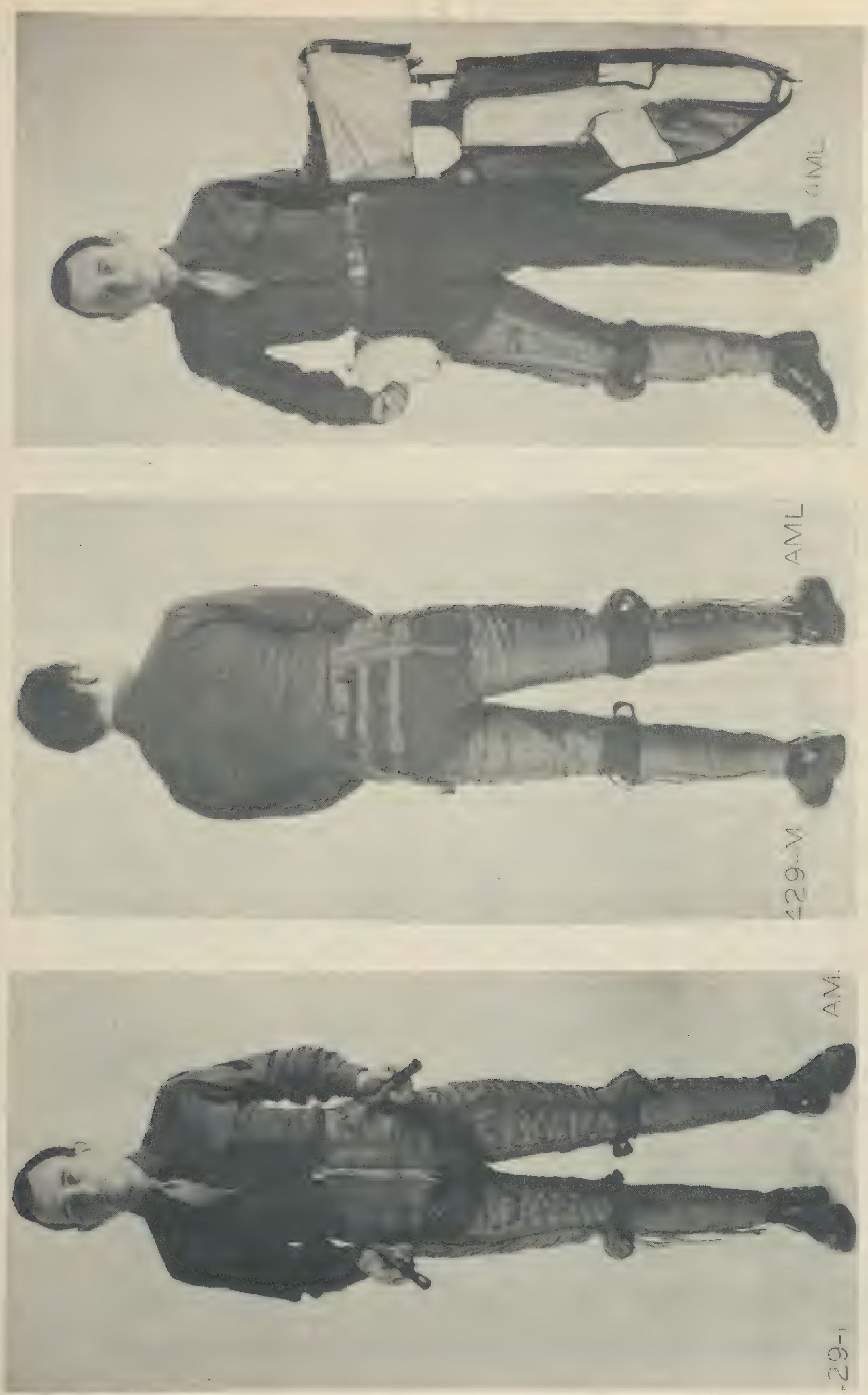


RAF PNEUMATIC ANTI G SUIT - SKELETON TYPE
NOTE DOUBLE INLET TUBE WITH SPLIT ABDOMINAL BLADDER

FIGURE 32

V. Sources of Air Pressure for the Pneumatic Anti-G Suit.

A. General requirements for an air pressure source for anti-G suits. Requirements for an adequate pressure source for anti-G suits have been best studied by Wood and Lambert. The following discussion is quoted from one of their reports:[63]

1. "The answer to this question (re minimum requirements) is dependent on a knowledge of three factors: (1) what is the minimum pressure needed for adequate suit protection; (2) what is the maximum allowable time for pressurization of the suit to its requisite pressure, and (3) what is the volume of air required to pressurize the suit to this pressure.

2. "It is generally agreed, as first suggested by the Wright Field group, that the current suit models must be inflated to a pressure of 4 p.s.i. in order to give a reasonable degree of protection. Therefore the pressure source should be capable of generating a pressure of 4 p.s.i. or more.

3. "In spite of considerable centrifuge experimentation on the problem there is still no exact data applicable to all types of G exposure as to the maximum period which can be allowed for inflation of an anti-blackout suit to the required pressure. Centrifuge and plane data indicate that optimum suit performance is attained when the suit inflation curve follows the onset of acceleration as closely as is practical. It is the consensus in the Mayo laboratory that 4 seconds should be the maximum allowable period for inflation of the suit to 4 p.s.i. in response to an instantaneous exposure to 6 G.

4. "The volume of ambient air required to pressurize an anti-blackout suit increases at altitude. The ambient air required to pressure the G-1 suit to 4 p.s.i. increased from 8 liters at 1,000 feet to 12 liters at 30,000 feet.

5. "Since 12 liters of ambient air may be required to pressurize current anti-G suits to 4 p.s.i., the average pump output required to pressurize these suits to this requisite pressure in 4 seconds is: 12 divided by 4, or 3 liters per second.

6. "The minimum requirements of the source for pressurization of anti-blackout suits are, therefore, that this source be capable under all possible tactical conditions of: (1) generating a pressure of 4 p.s.i., and (2) of maintaining an output of 3 liters of ambient air per second against an output resistance of 4 p.s.i. In setting these requirements it is assumed that maneuvers in which high accelerations of 4 G or more are attained are not performed at altitudes over 35,000 feet. At higher altitudes the rate of output of ambient air would have to be greater than that stated. If the cockpit of the airplane is pressurized, the cockpit pressure and temperature must be considered as the ambient pressure and temperature in fulfilling the requirements.

7. "It should be emphasized that the above are minimum requirements. For optimum G suit performance the pressure source should be capable of inflating the suit rapidly enough so that the curve of required suit pressure

does not at any time lag behind the G curve by more than one second. In general, a pressure source will fulfill this requirement if it is capable, under all possible tactical conditions, of generating a pressure of 15 p.s.i. and of maintaining an output of 6 to 10 liters of ambient air per second against 4 p.s.i."

B. Tanks of compressed gas.

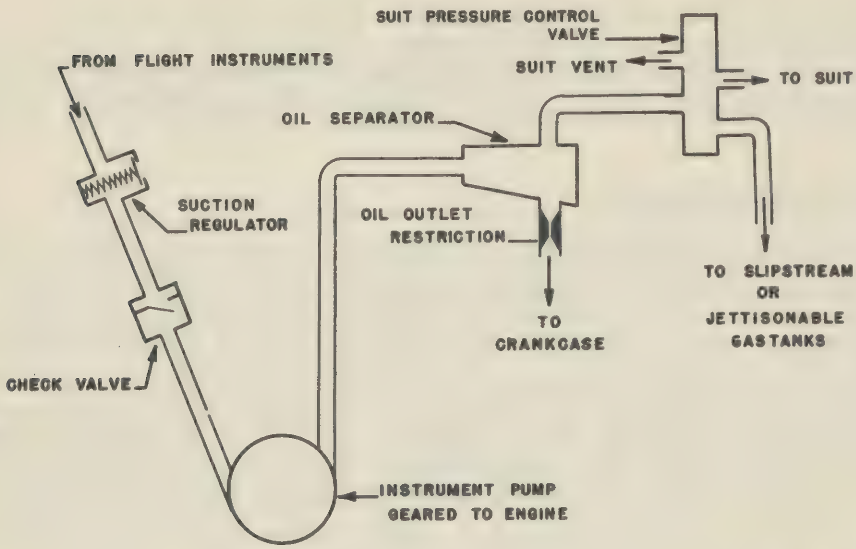
1. Air stored under pressure in tanks has often been used in experimental work on centrifuges to pressurize anti-G suits. The method is often a convenient one, particularly when it is desired to simulate the high valve inlet pressure which may occur when the pressure source is the compressor discharge of the jet engine. Tanks of carbon dioxide have been used as a pressure source for the Cotton aerodynamic anti-G suit by Cotton in Australia.[33] In general, the method has not been practical for routine usage in aircraft because tanks require space for installation, add weight to the airplane and demand a valve with no leakage at 1 G and no leakage other than that required to pressurize the suit at increased G. Tanks, along with electrically driven pumps, may have to be reexamined for possible use in rocket propelled aircraft in the future.

C. Pumps.

1. The vacuum instrument pump has been the standard source of air supply used by the Army Air Forces and by the US Navy for anti-G suits in conventional fighter aircraft. This pump was designed primarily to provide suction to power the gyroscopic flight instruments. The output side of the pump, originally led overboard, is now used to pressurize the anti-G suit and in many cases the auxiliary fuel tanks. In the standard installation the vacuum line from the pump leads to the flight instruments on the instrument panel. A suction relief valve in this line is adjusted to regulate suction at minus four to minus five inches of mercury pressure. Oil laden air from the pump passes through an oil separator which removes some of the oil and returns it to the crank case of the engine. Air from the oil separator passes to the pressure regulating valve for the G suit to be metered to the suit during increased positive G. (Figure 33a). Since the pump was not designed to pressurize the anti-G suit, its efficiency in this regard bears examination. Studies of this system have been carried out principally by the Mayo Aero Medical Unit. Variations in the suction the pump is producing, in the pump itself, in the oil separator, and in the interconnecting lines can affect the volume and pressure available to a G valve in this system.

a. The vacuum instrument pump is a rotary oil type pump, the output of which is directly proportional to (1) the r.p.m. of the pump and (2) the absolute pressure at the pump inlet. The following discussion by Wood and Lambert[63] relates these two variables to aircraft conditions: "In the plane the r.p.m. of the pump, and hence the output of the assembly, is determined by the r.p.m. of the plane engine. Thus the pump output available

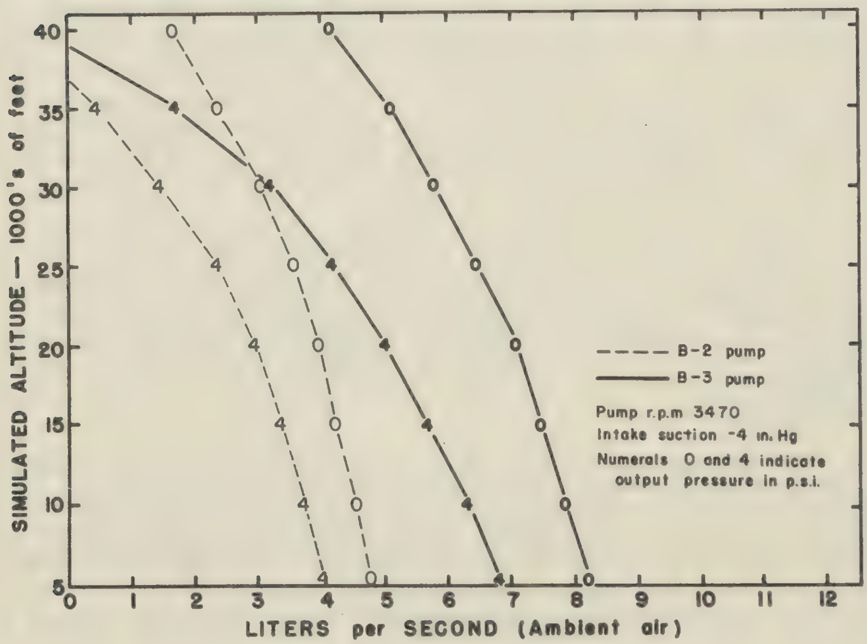
SCHEMATIC DIAGRAM OF THE INSTRUMENT PUMP ASSEMBLY
FOR G-SUIT INFLATION IN AIRCRAFT



FROM WOOD AND LAMBERT
CAM REPORT # 442

A.

COMPARISON OF THE EFFECTIVE OUTPUTS OF THE B-2 AND
B-3 INSTRUMENT PUMPS AT VARIOUS ALTITUDES



FROM WOOD AND LAMBERT
CAM REPORT # 442

B.

FIGURE 33

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for suit inflation may vary considerably in different type maneuvers. In the plane the absolute pressure at the intake of the pump is determined by (1) the altitude, (2) the flight instrument suction regulator, and (3) the amount of resistance to airflow in the intake line to the pump. In all type planes and independent of the altitude within limits, the flight instrument suction regulator maintains the pressure of the flight instrument at about four inches of mercury below ambient pressure. However, due to the considerable and variable resistance to airflow in the input line to the pump, the actual suction at the pump is always greater than four inches of mercury. Measurements in several different type planes have yielded values varying from 5 to 12 inches, i.e. 120 to 300 mm. mercury negative pressure at the pump. This necessity of maintaining an intake suction precludes the possibility of obtaining a good performance at altitude from any instrument pump assembly. No vacuum instrument pump can maintain a reasonably adequate positive pressure output when it is required to maintain an intake suction of over 100 mm. Hg in the face of a total barometric pressure which may fall to 140 mm. Hg. (40,000 feet). It is apparent from these considerations that the absolute intake pressure at the pump may fall from 660 mm. Hg. at sea level to 40 mm.Hg at 40,000 feet. This would result in decrease in the effective output of the instrument pump valve assembly of 94 per cent. At 18,000 feet, the output of the pump would be reduced about 50 per cent."

b. Two types of pumps are in use in fighter aircraft. The smaller type is denoted B-11 by the AAF (Navy B-2), the larger is called type B-12 (Navy B-3). Figure 33b. illustrates the effect of altitude on the performance of these two pumps when operated at 3470 r.p.m. with intake suction of minus four inches of mercury. The effective output of the B-11 (B-2) pump is about two-thirds that of the B-12 (B-3) pump. The B-2 pump under these circumstances maintained an output of three liters per second against a resistance of 4 p.s.i. up to approximately 20,000 feet; the B-3, to 30,000 feet.[63]

c. Without inlet suction, performance is better. Wood et al measured the time required to inflate a Z-1 suit to 4 p.s.i. at altitudes from 5,000 to 40,000 feet when the pumps were run at 3470 r.p.m. without input suction.[41] This inflation time at 40,000 feet was 4.5 seconds in the case of the B-11 (B-2) pump and 2.9 seconds with the B-12 (B-3) pump. The authors considered the B-11 pump used without input suction adequate to 40,000 feet, and the B-12 pump in these circumstances adequate to "all altitudes which man can attain with conventional oxygen equipment."

d. Another variable studied by the Mayo group which can influence performance of the vacuum instrument pump is the size of the oil vent orifice of the oil separator. Wood and Lambert[63] state that approximately 150 cc. of oil are vaporized into instrument pump air per hour, and that 75 to 80 per cent of this oil is reclaimed and returned to the crankcase by the oil separator. The amount of air which escapes through the oil outlet of the oil separator is restricted by an orifice located in the oil outlet port of the separator. The size of this orifice varies with the different oil separators thus:

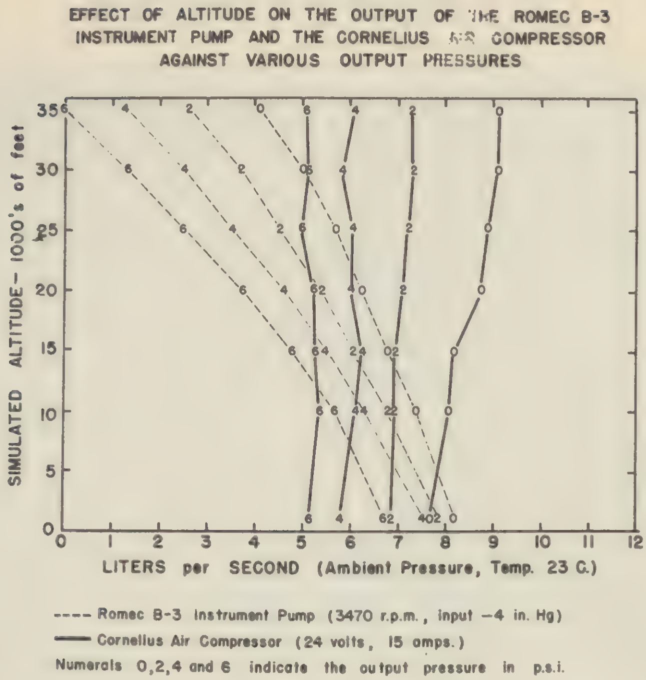
Oil separator type	Part No.	Dimension of oil outlet restriction		
		Internal diameter, inches	Length, inches	Area, inches^2
Army B-12	AN 6121-2	0.062	3/64	0.00302
Navy centrifugal	47089-1	0.070	4/64	0.00385
Navy centrifugal	46975-1	0.128	4/64	0.01287

e. Use of the Navy type with an oil outlet of 0.128 inches diameter reduces performance of the system as compared with use of either of the other two separators. The use of the oil separator with a 0.128 inch oil outlet reduced performance of one particular assembly with the B-2 pump by more than 10,000 feet (Figure 34B).

f. Information of this type was obtained in flight tests carried on in an FM-2 airplane by the Ryan Aeronautical Company under the direction of C. W. Terry.[57,70] Results are in general agreement with laboratory data quoted above. Two graphs from the Ryan report are reproduced as Figures 35 and 36. In these graphs suit pressure in p.s.i. is plotted against time in seconds. Data are shown for the B-2 and B-3 pumps at engine r.p.m. values of 2100 and 2500. The data can be tabulated thus:

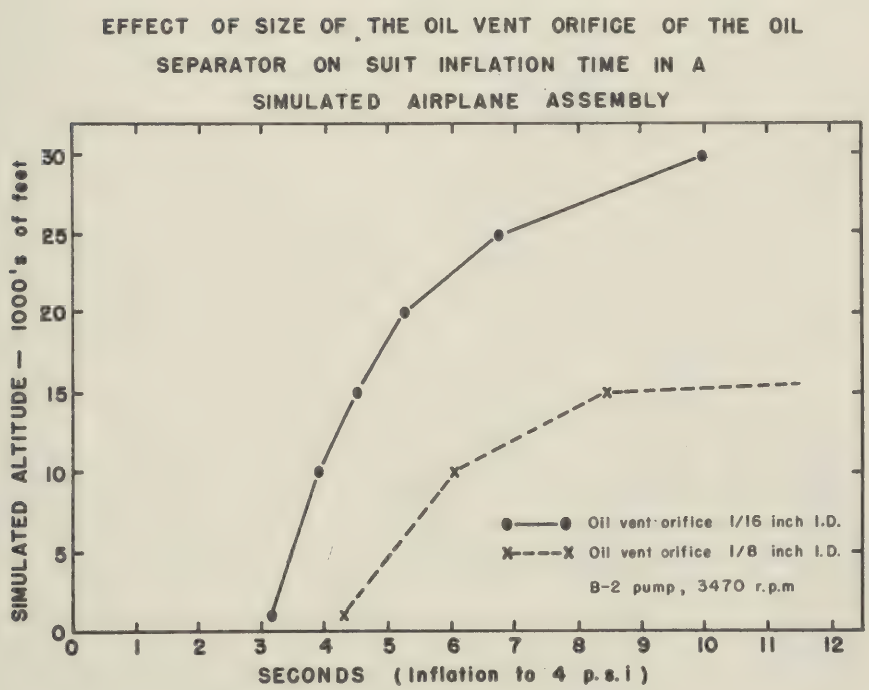
Altitude, feet	Time in seconds to reach 4 p.s.i. suit pressure			
	B-2 pump (Army B-11)		B-3 pump (Army B-12)	
	Engine r.p.m. 2100	Engine r.p.m. 2500	Engine r.p.m. 2100	Engine r.p.m. 2500
10000	3.8	3.6	2.4	2.3
15000			2.9	2.8
20000	5.1	4.3	3.6	3.4
25000	10.4	7.9	4.7	3.8
30000			7.0	5.8

g. Wood and Lambert conclude that on the basis of the minimum requirement of maintaining an output of three liters of ambient air per second against an output resistance of four p.s.i., the instrument pump assembly becomes inadequate for pressurization of the G suit above 20,000 feet when the B-2 or B-11 pump is used and above 30,000 feet when the B-3 or B-12 pump is used.[63]



A

FROM WOOD AND LAMBERT
CAM REPORT #442



B.

FROM WOOD AND LAMBERT
CAM REPORT # 442

FIGURE 34

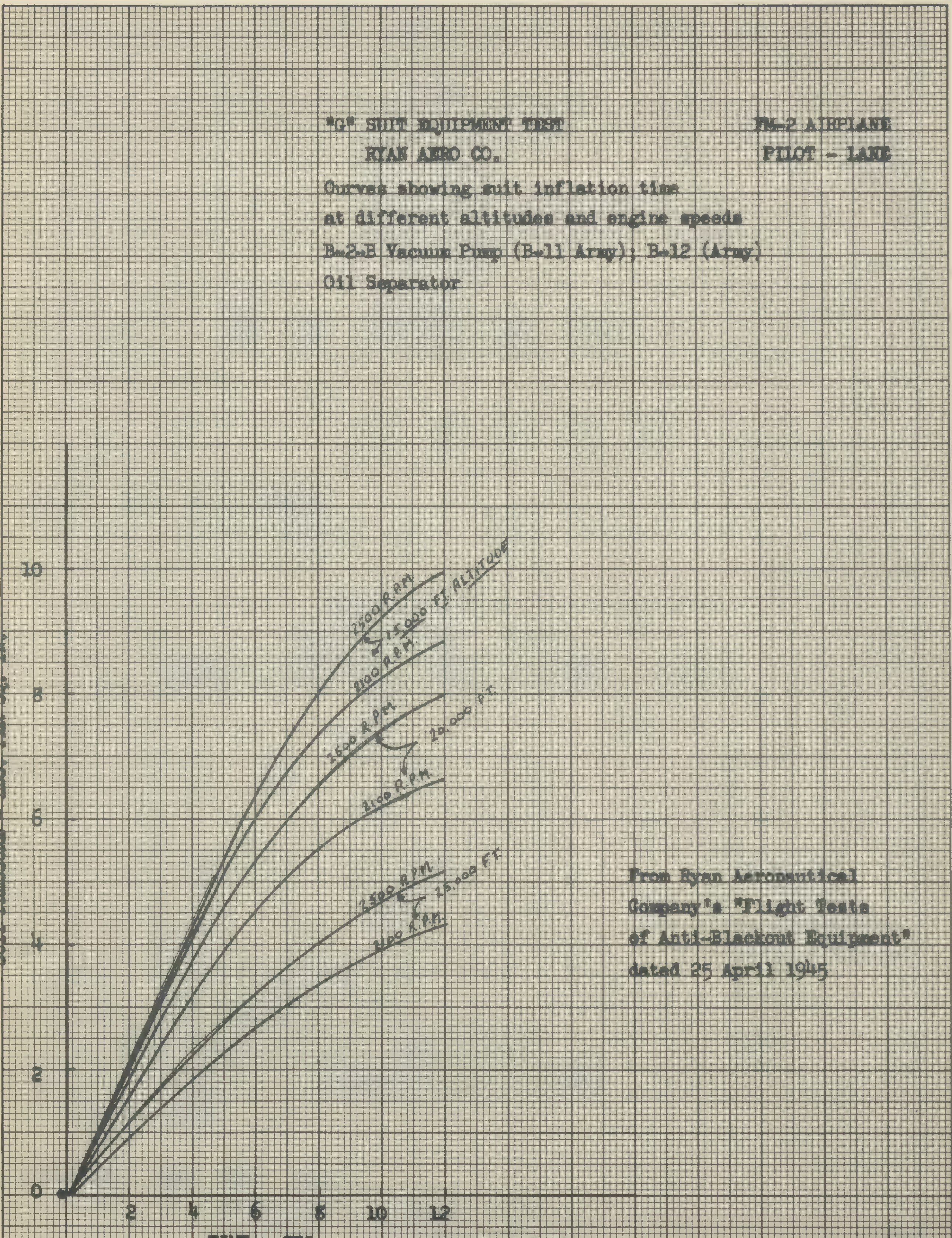


FIGURE 35.

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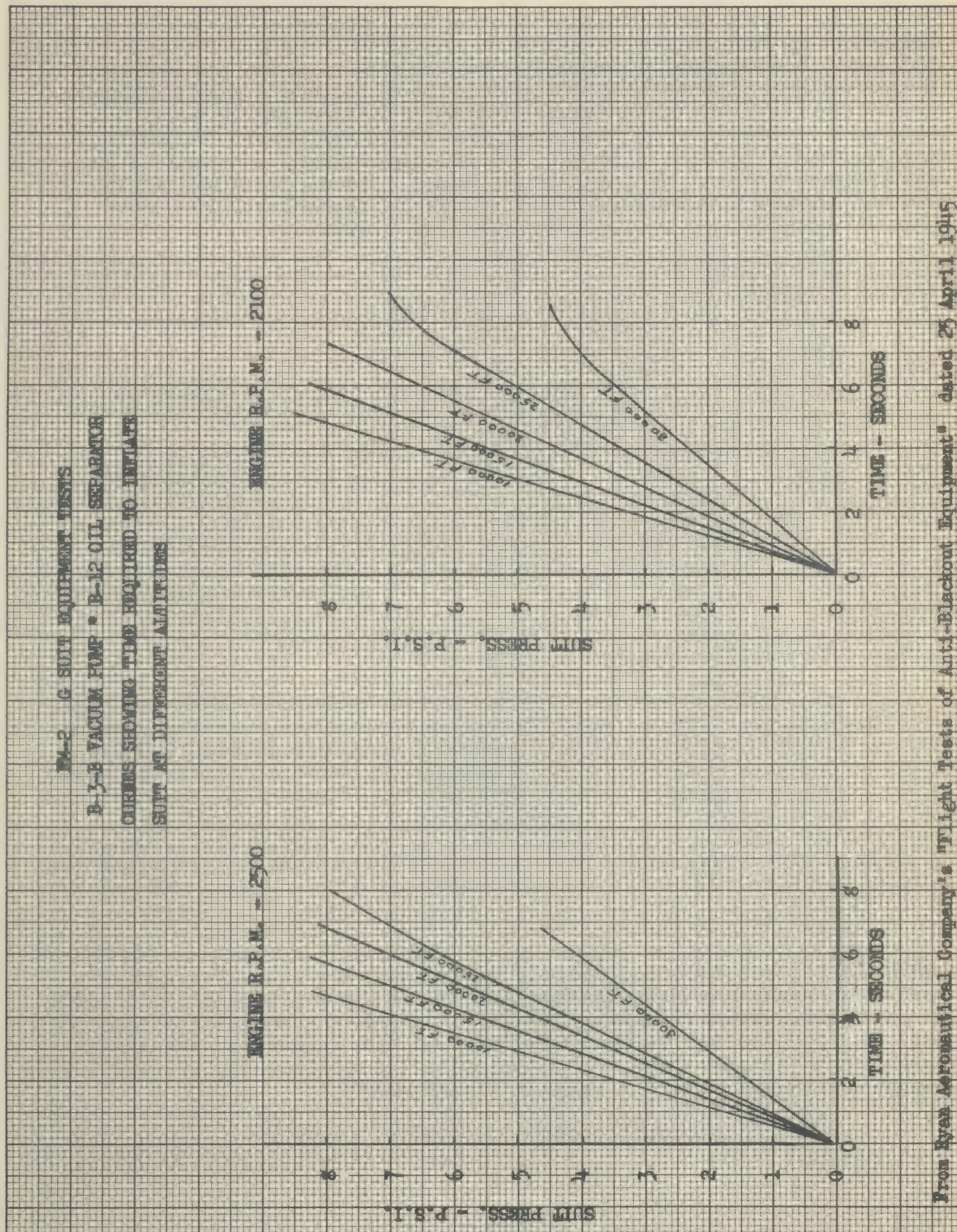

M-2 G SUIT EQUIPMENT TESTS
B-3-B VACUUM PUMP * B-12 OIL SEPARATOR
CURVES SHOWING TIME REQUIRED TO INFLATE
SUIT AT DIFFERENT ALTITUDES
ENGINE R.P.M. - 2100
ENGINE R.P.M. - 2500
SUIT PRESS. - P.S.I.
TIME - SECONDS
10000 FT
15000 FT
20000 FT
25000 FT
30000 FT
From Ryan Aeronautical Company's "Flight Tests of Anti-Blackout Equipment" dated 25 April 1945

FIGURE 36.

h. Acting only on these data and this conclusion, one would be inclined to condemn the vacuum instrument pump as an air source for anti-G equipment. However, the important fact remains that in actual use both in service tests and in combat, the present equipment has been entirely adequate for the types of flying being done. No cases of failures attributed to poor performance of the pump have been reported, as Wood and Lambert recognized. This is probably due in part to the fact that high values for positive G are less frequent at higher than at lower altitudes. Indeed, there has really been no G problem with conventional aircraft above 30,000 feet, G at these altitudes being limited to low values by buffet limitations.

i. These data do lead to certain valid recommendations:

(1) The B-3 (B-12) pump should be used in preference to the B-2 (B-11) pump.

(2) The oil separator with the 1/16 inch oil outlet should be used in preference to that with an 1/8 inch oil outlet.

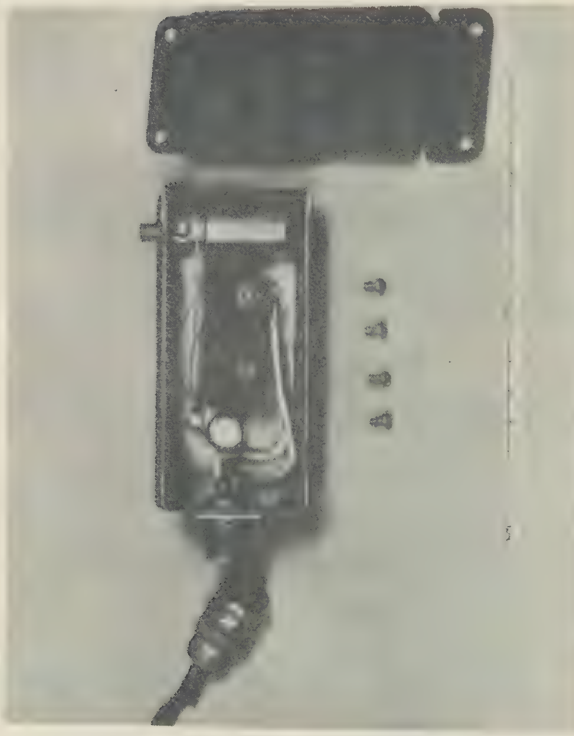
(3) Should the type of maneuvers used begin to result in complaints of slow suit inflation at high altitudes, the situation could be corrected by providing electrical power for the gyroscopic instruments and using the B-12 pump without inlet suction, or by placing a G-activated valve on the inlet side of the vacuum instrument pump to open the pump inlet to ambient air at accelerations above three or four G.

2. The Cornelius pump.

a. Anticipating a possible need for an independent pressure source for anti-G equipment, the Cornelius Company of Minneapolis, Minnesota, working with the Mayo Aero Medical Unit, developed an electrically driven oscillating diaphragm type pump with pressure and volume output adequate for pressurization of the G suit to altitudes in excess of 40,000 feet (Figure 37). The first model of the compressor which was used for this purpose was employed to pressurize the arterial occlusion suit. During tests at Eglin Field, failure of the metal diaphragm and test valve occured.[67] Subsequent refinement has resulted in a pump assembly with better endurance characteristics. One unit, tested at the Mayo Aero Medical Unit, satisfactorily completed 20 hours continuous operation against a pressure of four p.s.i. without failure. The pump weighs nine pounds and measures six by 10-1/2 by 13-1/2 inches. The 24 volt electric motor draws from 10 to 18 amperes over the range of operating conditions (output pressure, altitude) encountered in pressurization of G suits. Free air flow from the compressor is nearly constant at altitudes from sea level to 35,000 feet and varies from eight liters per second when the pump is discharging to ambient air to 4.5 liters per second when the pump is operating against a gauge pressure of six p.s.i. (Figure 34A).[63]

b. The compressor operates satisfactorily over a temperature range of +160 degrees Fahrenheit to - 45 degrees Fahrenheit (+71 degrees Centigrade

CORNELIUS PUMP, G SWITCH, AND RELAY



G-ACTIVATED MICRO-SWITCH

FIGURE 37

to minus 43 degrees Centigrade). It should probably not be started cold at temperatures below minus 45 degrees Fahrenheit. When warm at the start, it has operated satisfactorily for 10 seconds out of each minute at minus 60 degrees Fahrenheit (minus 51 degrees Centigrade). If the compressor is used only during periods of acceleration and is not subject to prolonged continuous running, the fan on the motor is not necessary.

c. When used to pressurize the G suit, the compressor operates only during increased positive G. The electrical circuit is closed by a G activated microswitch which activates a relay (Figure 37).

d. The Cornelius compressor has been used extensively on the centrifuge and in an aircraft for test purposes, but has not seen general service usage.

D. <u>The compressor discharge of the jet engine.</u>

1. Jet engines thus far used carry no counterpart of the vacuum instrument pump. The compressor of the jet engine provides air under pressure and is a logical pressure source for the anti-G suit. The adequacy of the pressure discharge of the I-40 engine in the P-80 airplane for pressurizing the G suit has been evaluated.[11]

a. The tubing which conducts air from the compressor passes forward through the plenum chamber to the subcockpit space and enters the cockpit through a bulkhead fitting in the floor behind the seat. The G valve is mounted in the cockpit to the left of the pilot's seat.

b. Arrangements were made to measure valve inlet pressure and temperature, and, in other tests, free air flow available to the valve. The work was done in a P-80 airplane powered by a General Electric I-40 turbo-jet engine.

c. Results:

(1) Inlet pressure to the valve versus engine r.p.m. at various altitudes. Inlet pressure measurements made with this particular valve (the JP-1, see below) were not made under strictly static conditions since this valve allows a small flow of air in level flight. (Figure 55 Table 2). Since this same air flow occurs with this valve during increased positive G after the suit has been inflated to the pressure demanded by the acceleration, the valve inlet pressures here measured represent the maximal pressure available for suit pressurization when this valve is used. Valve inlet pressures at various engine r.p.m. values, measured in a ground run and in level flight at altitudes of 5000, 10000, 20000, 30000 and 38000 feet are plotted in Figure 38 and discussed below.

(2) Air flow available to the pressure regulating valve in the P-80 airplane. The flow meter was attached to the air line in the airplane with the air filter and G valve excluded from the system. Thus free air flow available to any valve which receives air from this source was measured. These data, obtained in a ground test run, are plotted against engine r.p.m. in Figure 39 and discussed below.

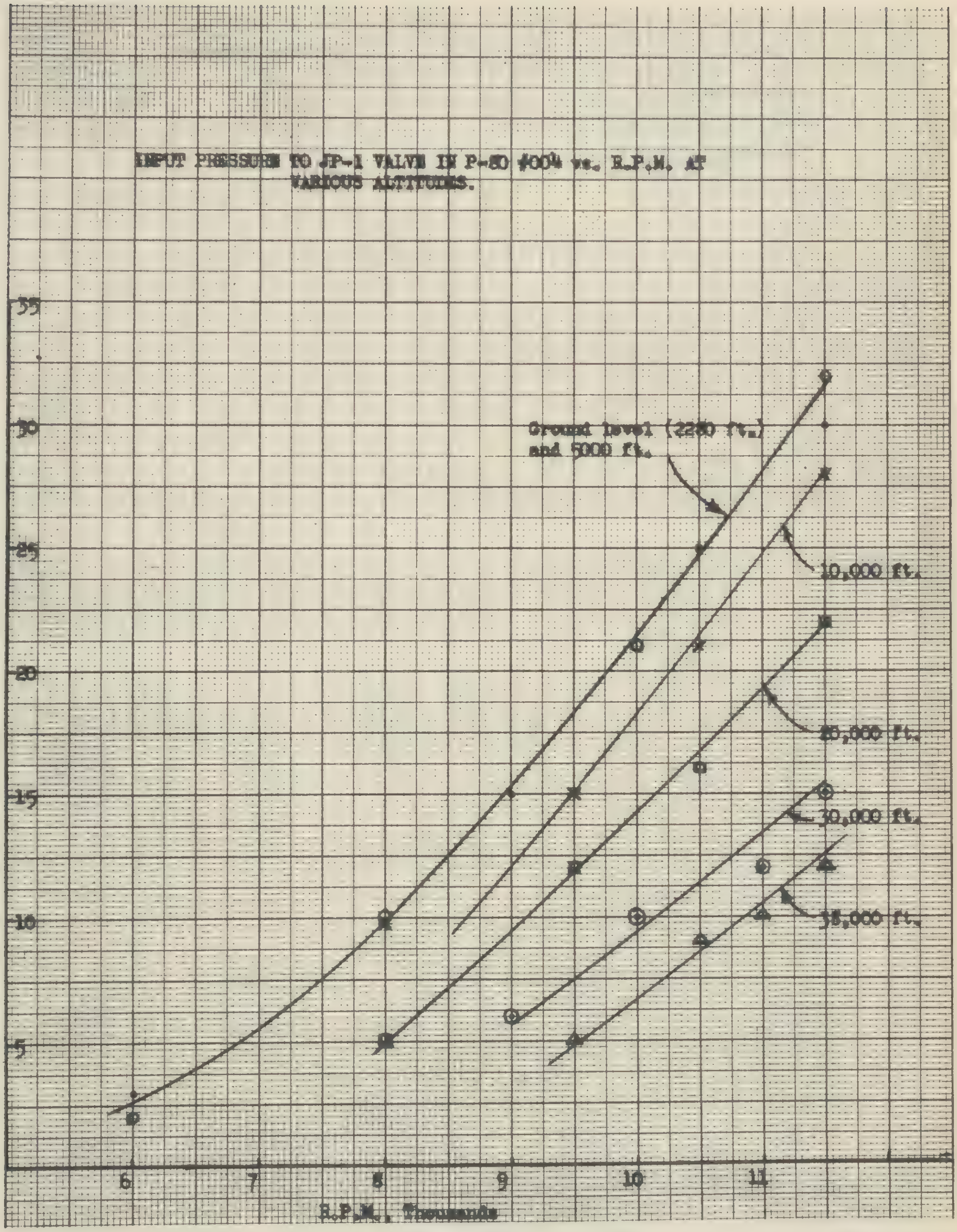


Figure 38

4528 A M L

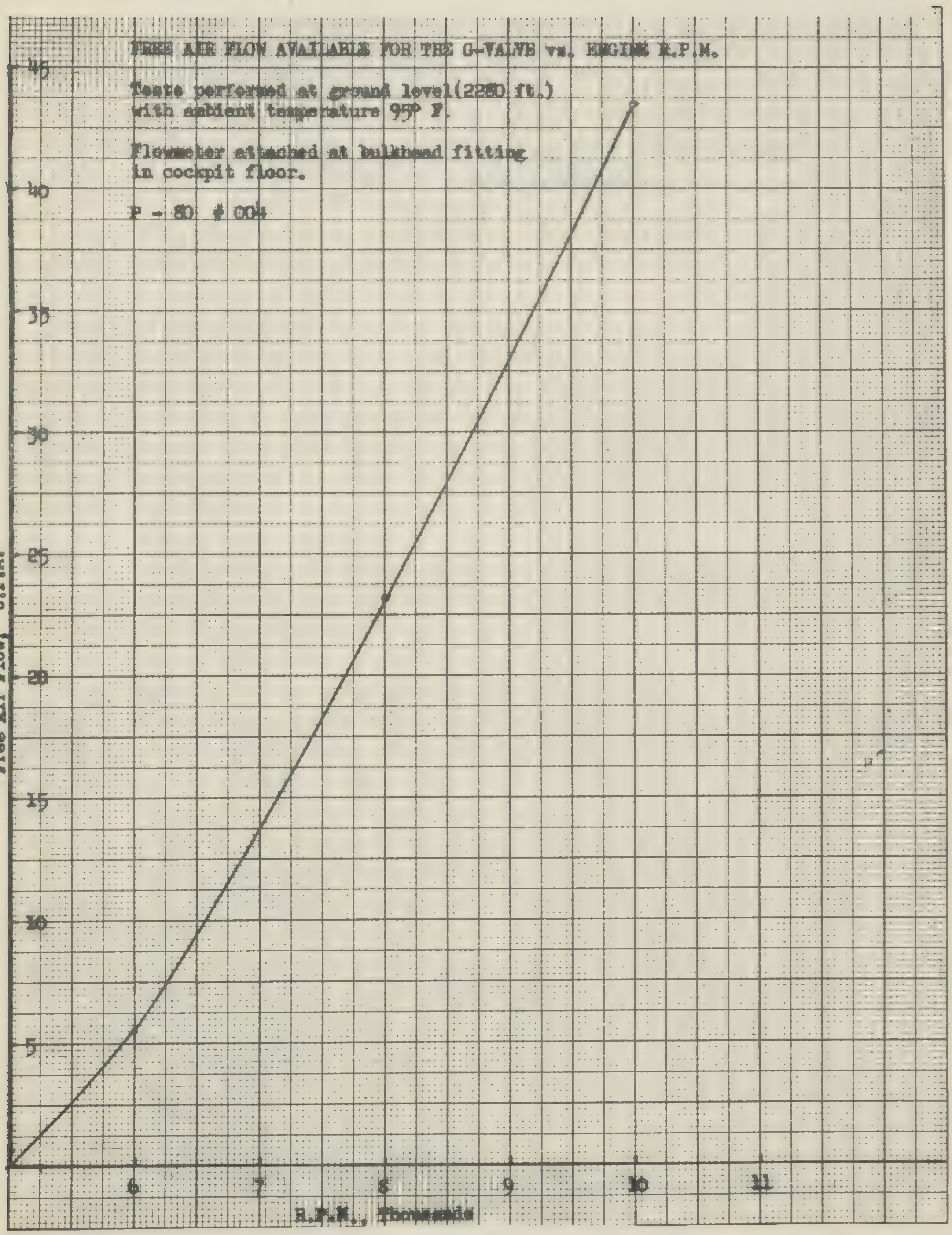

FREE AIR FLOW AVAILABLE FOR THE G-VALVE vs. ENGINE R.P.M.
Tests performed at ground level(2280 ft.)
with ambient temperature 95° F.
Flowmeter attached at bulkhead fitting
in cockpit floor.
P - 80 # 004
45
40
35
30
25
20
15
10
5
6
7
8
9
10
11
Free Air Flow, C.F.M.
R.P.M., Thousands

Figure 39

(3) Inlet air temperatures to the JP-1 valve in the P-80 airplane ranged from 33 degrees Centigrade (91 degrees Fahrenheit) to 40 degrees Centigrade (104 degrees Fahrenheit) with one isolated reading of 45 degrees Centrigrade (113 degrees Fahrenheit) noted in a ground run at 11,500 r.p.m. These readings were taken in a ground run and in level flight at varying r.p.m. values and altitudes up to 38,000 feet. It was noted in the ground test that the piston of the valve could be held fully down, thus allowing maximal air flow through the system, for 60 seconds without any measurable increase in air temperature.

d. Discussion:

(1) The question arises, are the pressure and air flow of compressor discharge air in the P-80 airplane adequate to supply the anti-G installation? Minimum requirements for an air source to supply this system, as suggested by Wood and Lambert,[63] can be stated as (a) a minimum available pressure of 4 p.s.i. and (b) an air flow of at least three liters of ambient air per second (6.4 c.f.m.) against an output resistance of 4 p.s.i. Such a pressure source will inflate a G suit to a pressure of 4 p.s.i. in 3-1/3 seconds when its volume at 4 p.s.i. pressure is 10 liters. Again, for emphasis, these are minimal requirements. Greater air flow will fill the suit more rapidly and decrease the lag between onset of acceleration and suit inflation. Before applying this criterion to these data one must note that use of a pressurized cockpit will raise the minimal requirement for available pressure by the magnitude of pressure differential between cockpit and ambient air, since the compressor is outside the pressurized region and the suit must be inflated to given pressures in excess of cockpit pressure. Hence, if a pressure differential of 2.75 p.s.i. between cockpit and ambient pressure is used as recommended by the Aero Medical Laboratory, Engineering Division, ATSC, the minimal required gauge pressure required of the compressor air becomes 6.75 p.s.i. Examination of Figure 38 shows that gauge pressures of 6.75 p.s.i. are available in the unpressurized cockpit at engine r.p.m. values of 7300, 8400, 9300 and 10000 at altitudes of 5000, 20000, 30000, and 38000 feet, respectively. Since these r.p.m. values are in the lower part of the range which may be expected to be commonly used at these altitudes, it is concluded that the pressure of compressor air from the G suit installation meets the minimum requirements. At the higher r.p.m. values which are more often used in flight, the pressure is entirely adequate. Reference to Figure 39 will show that a free air flow of 16.2 c.f.m. (7.64 liters/second) was measured when engine r.p.m. in a ground run was 7300. Available suit pressure in this circumstance, as shown in Figure 37, is 6.75 p.s.i. These data indicate that inflation of the suit will still be rapid when available pressures are as low as 4 p.s.i. in a cabin pressurized at a differential of 2.75 p.s.i. It is concluded that compressor discharge air from the I-40 engine in the P-80 airplane, with the plumbing currently used in production models, provides air with adequate pressure and flow for the anti-G assembly.

(2) The data for inlet air temperature require further discussion. Since compressor discharge temperature may reach 300 degrees Centigrade (572 degrees Fahrenheit), it has been stated by some who have considered the problem that dissipation of heat from the air while en route to the G valve would not be rapid enough to cool the air to acceptable temperatures. This opinion received support from a report of a pilot who stated that he had occasion to feel the air escaping from the tank port of an M-2 G valve during a cross

country flight at 35000 feet altitude and found it too hot for the bare hand to tolerate. It must be remembered that the M-2 valve allows a much greater rate of air flow in level flight than does the JP-1 valve. It can, therefore, be assumed that a given molecule of air remains in the line between compressor and valve a shorter time than in the case in which the JP-1 valve or any other valve which has similar air loss in level flight is used. Therefore it has less time in which to dissipate its heat. This reasoning probably explains the relatively low inlet air temperatures encountered with use of the JP-1 valve. Moreover, air entering the G suit will expand further and lose heat in this process. Hence suit air temperatures can be expected to be lower than valve inlet air temperatures. Reports from pilots indicate that neither the sensation of heat nor of cold is felt when the suit is inflated in flight when the JP-1 valve is used. Indeed, no complaints of heat with suit inflation have been received even when the M-2 valve has been employed. Only one filling of air reaches the suit. In view of the foregoing, it can be stated that use of a valve with air loss equal to or less than that occurring in level flight with the JP-1 valve will eliminate need for special efforts to cool the air for the anti-G installation in the P-80 airplane.

VI. Pressure Regulating Valves for Pneumatic Anti-G Suits.

In the course of development of different anti-G suits, several G-controlled, G-compensated, air pressure regulating valves have been designed to meter air to the suits. Several of these, some of which are obsolete but which embody useful principles of design and some of which are in use at present, will be described in the following paragraphs.

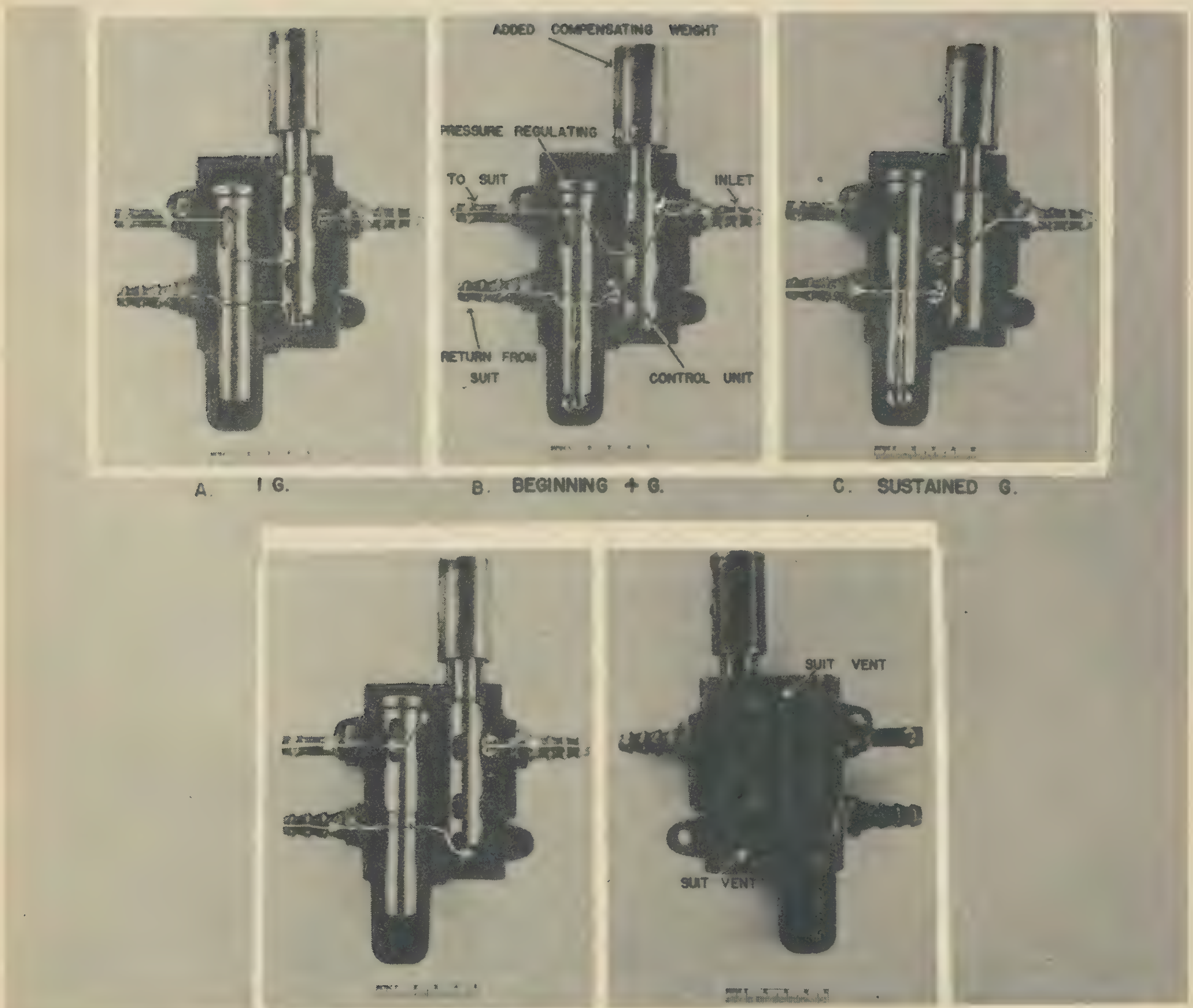
A. The Heald valve.

1. The Heald valve was designed in 1942 by Mr. Henry Wilder of the Heald Engineering Company and Mr. David Clark of the David Clark Company to pressurize some early suits made by Mr. Clark. It is a balanced-piston cylinder type valve with such close tolerances between pistons and cylinder that it will withstand inlet pressures up to 60 p.s.i. without leakage of air. The valve has two pistons (Figure 40).

2. The piston of the control valve is supported by an inner coiled spring and carries a compensating weight on top. The purpose of this part of the valve is to control the passage of air to the other, pressure regulating piston-cylinder combination. Until this valve is exposed to sufficient acceleration that the combined weight of the control valve piston and superimposed compensating weight is great enough to overcome the coiled spring, the piston remains in the up position, and the inlet air is blocked (Figure 40A). When a G level is reached at which the reverse holds true the piston and weight move downward, causing the milled-out areas to straddle the land and allow air to pass to the pressure regulating side of the valve (Figures 40B and 40C). Thus the G at which the control valve trips is determined by the relationship between the total mass of its moving parts (piston and weight) and the strength of the coiled spring.

3. The piston of the pressure regulating valve is held in the down position by a light coiled spring above. In this position, milled-out areas in it straddle a land and permit air from the control valve to enter a chamber which leads to the port to which the G suit line is attached (Figures 40A and 40B). A return line from the airline to the suit leads to a second port which opens into another chamber of the pressure regulating valve. In this way, air at suit pressure is led to the chamber beneath the pressure regulating piston where it exerts force upward. The magnitude of this force is equal to the air pressure in this chamber (suit pressure) multiplied by the end area of the piston. When this force is great enough to exceed the weight of the piston multiplied by the G plus the small force exerted by the coiled spring, the piston moves upward, stopping further inflow of air to the suit (Figure 40C). Since the pressure necessary to raise the piston depends on the G to which the valve is exposed, the valve is G compensated and delivers greater pressure the greater the G. Actually, unless the system were air-tight, the piston would seek an intermediate position, supplying a small amount of air to replace that lost by the leakage.

4. When the episode of G has passed, the control piston, impelled by its coiled spring, returns to the up position and the pressure regulating piston, impelled by the pressure beneath it, moves to the fully up position (Figure 40D). Air can now escape from the suit by reversing its course through



A. 1 G.　B. BEGINNING + G.　C. SUSTAINED G.

D. RETURN TO 1 G.　E. REAR VIEW

HEALD PRESSURE REGULATING VALVE FOR G-SUITS

FIGURE 40

the suit port and going through a slot in the housing opposite the topmost compartment of the pressure regulating valve, and by passing through the return port to the control valve side and out the slot in the housing opposite the lower most compartment of the control valve (Figures 40D and 40E). When most of the air has left the suit, the pressure regulating piston moves downward to its original position, closing the first method of escape of air and leaving the second for escape of the remaining air (Figure 40A). The slots for escape of air from the suit are visible in the rear view, Figure 40E. The Heald valve has never been used in aircraft, but several were used in early centrifuge studies. The pressure it delivers varies directly with the mass of the pressure regulating piston and inversely with its end area. The chief disadvantage of the Heald valve is the fact that its close tolerances caused it to stick frequently. Aside from this fact, its function was satisfactory.

B. <u>The Cornelius valve for the arterial occlusion suit.</u>

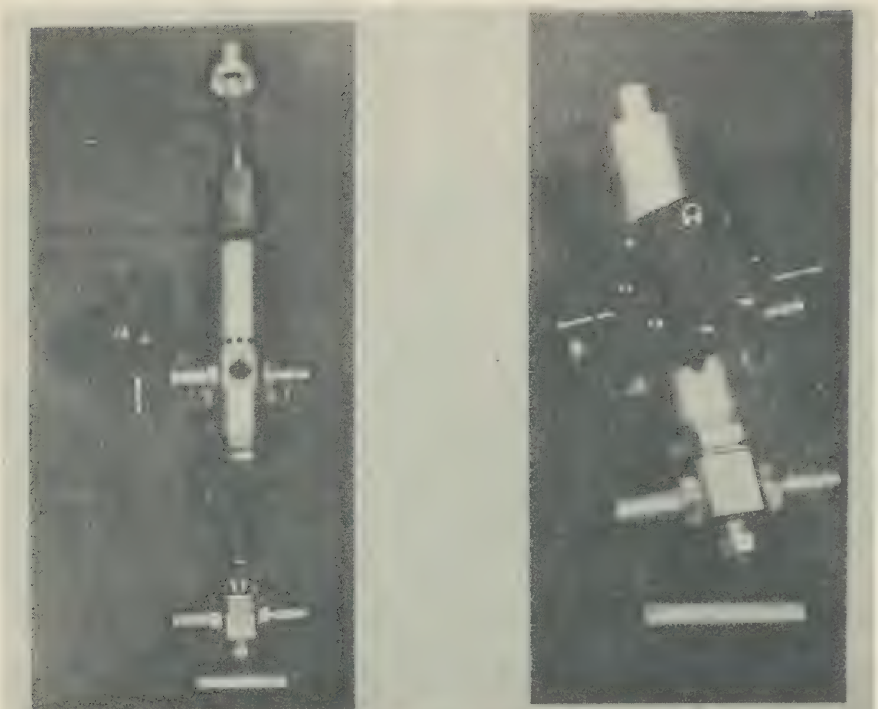
1. This valve, designed by Mr. Richard Cornelius of the Cornelius Company, Minneapolis, Minnesota, was built to receive air from the Cornelius pump and G switch combination (see section V, paragraph C-2) and to pressurize the arterial occlusion suit. The arterial occlusion suit required that air be delivered at three different pressure rates: 4 p.s.i. plus 1 p.s.i./G for the thigh cuffs, 1 p.s.i. plus 1 p.s.i./G for the abdominal bladder and a constnat pressure of from 4 to 5 p.s.i. for the arm cuffs (Figure 10). Flow of air into the valve is controlled by a G activated microswitch which actuates the motor of the Cornelius pump at accelerations of 2 G and greater (Figure 41C). Suit pressure is regulated as follows (Figure 41):

2. The pressure to thigh cuffs. Air from the pump passes through the inlet port of the valve into the chamber of a spring-loaded G compensated, poppet-type blow-off valve (Figures 40A and 40B). The poppet is seated above until air pressure within the chamber is great enough to raise it. The pressure required to raise the poppet and vent the valve is determined by the weight of the poppet and the force exerted by its coiled spring. This combination is set for 4 p.s.i. plus 1 p.s.i./G. Air from this chamber is led directly to the thigh cuffs.

3. The pressure to abdominal bladder. Air in the chamber of the G compensated, spring-loaded, poppet type blow-off valve described in the preceding paragraph acts against a spring-loaded diaphragm, the spring tension and area of which are designed so that a pressure of three pounds per square inch is required for it to open (Figures 41A and 41B). Air which passes through this orifice is led to the abdominal bladder of the suit. Abdominal bladder pressure remains 3 p.s.i. less than thigh cuff pressure and is delivered at the rate of 1 p.s.i. plus 1 p.s.i. per G.

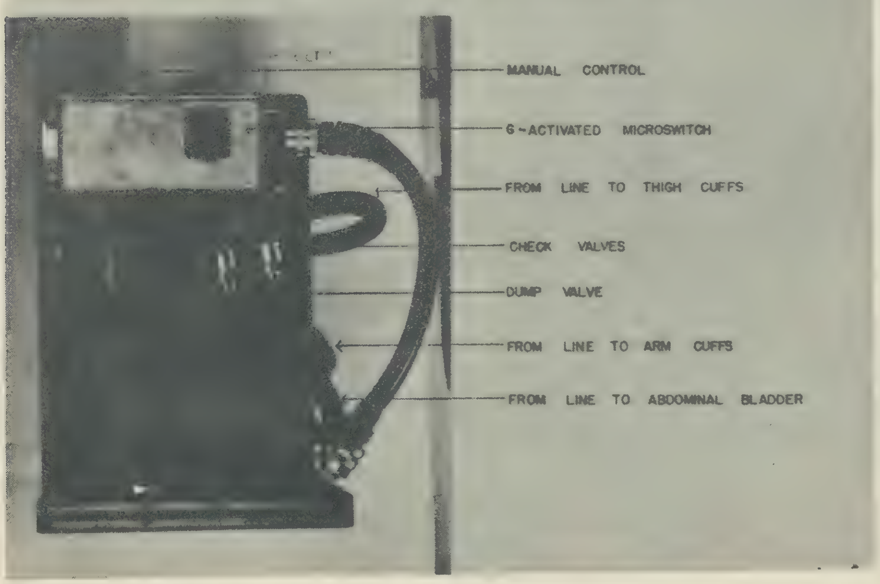
4. A second reduction valve, set to maintain an output pressure of 4 to 5 p.s.i., receives air from the master poppet valve and delivers it to the arm cuffs (Figures 41A and 41B).

5. A G activated dumping valve is an integral part of the G switch (Figure 41C). Three air lines, one from each bladder group, lead to the dump



A. B.

VALVE SYSTEM, EXPLODED AND ASSEMBLED VIEWS.



C.

G SWITCH AND DUMP VALVE

CORNELIUS 3 PRESSURE VALVE SYSTEM FOR THE ARTERIAL OCCLUSION SUIT

FIGURE 41

valve. The dump valve, open to ambient air unless the system is exposed to 2 or more G, provides for emptying the suit. At 2 G, the dump valve closed when the G switch trips, closing the connection with ambient air and allowing the suit to be pressurized. Check valves in the lines from arm cuffs and abdominal bladder prevent the higher pressure air from the line connected with the thigh bladders from passing back into the other bladders.

6. This valve system has been used extensively in centrifuge test work, and was given aircraft trials at the AAF Proving Ground Command, Eglin Field, Florida, in September and October of 1943.[67] The valve was found reliable in the aircraft tests, but the pump and G switch failed occasionally. The pump has been further developed and is now considered reliable, and an improved G switch (though it does not incorporate the dump valve necessary for pressurization of the arterial occlusion suit) is now available (see section V, paragraph C-2).

C. <u>The General Electric valve and valve regulator.</u>

1. The General Electric Company, in the persons of Mr. David C. Spooner and R. J. Sertl, began in 1944, to work in coordination with Dr. Harold Lamport in the design of a pressure regulating valve for G suits. Though the resulting valves could be adjusted to deliver air under pressures suitable for Lamport's pneumatic-lever suit (see section IV, paragraph D-11) they should not be considered as being specifically for the PLS since they can also be set to deliver lower pressures if this is desirable. The General Electric valves differ from other G valves thus far developed in that the flow of air is controlled by a solenoid activated valve. Actuation of the solenoid is controlled by an air pressure regulator.

2. Figure 42 presents a schematic drawing taken from a report of Haglund, Engstrom and Wood[35] of Model P-321-11 in which the valve and pressure regulator were combined to form a single unit. Air enters a chamber from which two ports lead, one to the suit and one to the solenoid activated poppet exhaust valve. When the solenoid is unenergized, the exhaust valve is open. A Venturi tube in the valve inlet port directs air to the exhaust valve chamber and prevents pressurization of the suit. When the solenoid is energized, the exhaust valve is closed and the suit is pressurized. The solenoid is energized when the circuit of the pressure regulator is closed. The pressure regulator consists of a weight and air pressure controlled microswitch. The weight, supported by a coiled spring, tends to move downward during G and close the circuit. A sylphon, connected to the suit air line, is mounted below the lever to which the weight is attached. Pressurization of the suit pressurizes the sylphon which expands, lifts the weight and opens the circuit, de-energizing the solenoid and opening the exhaust valve. This allows air to escape from the suit, lowering suit and sylphon pressure. As a result, the circuit is closed again and air once more enters the suit. Thus suit pressure continually oscillates. Its frequency varies from 20 cycles per second at 3 G to 7 cycles per second at 9 G when the pressure source was a B-3 vacuum instrument pump at ground level (1,000 feet) operating at 3470 r.p.m.[35] It follows:

a. That the increment in suit pressure per G is directly proportional to the mass of the microswitch weight and inversely proportional to the end

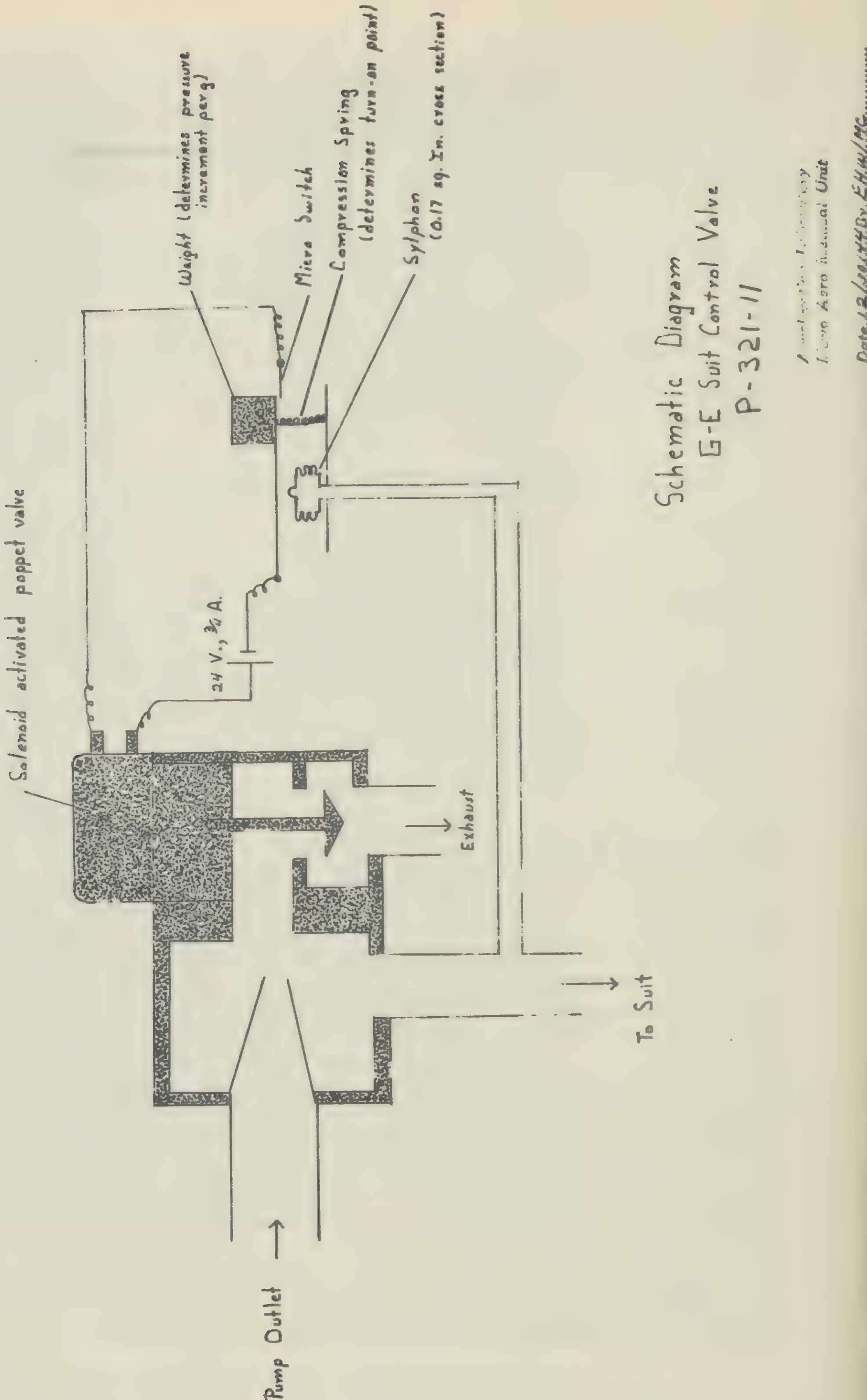


FIGURE 42

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area of the pressure control sylphon.

b. That the G required to first close the circuit depends on the relationship between the weight on the microswitch and the strength of the spring which supports it.

3. Tests at the Mayo Aero Medical Laboratory[35] indicate:

a. That the calculated pressures to be delivered to the suit correspond reasonably well with the mean pressures obtained in centrifuge tests and static tests in which acceleration was simulated by addition of calibrated test weights to the microswitch weight.

b. That pressure regulation was essentially the same when pump output varied from 1.6 to 6.4 liters per second though the frequency of oscillations decreased as pump output decreased.

c. That suit inflation time averaged 3.5 seconds at accelerations above 6 G and 5.8 seconds at accelerations below 4 G. This phenomenon of longer inflation time at lower G levels is undesirable.

d. That the pressure oscillations were noticable to one wearing a G suit.

4. In an effort to correct some of the defects noted in Model P-321-11 and to provide for pressurization of auxiliary fuel tanks when this function is needed, a new system was devised. The pressure regulator and the valve were made separate components in order that the valve might be mounted some distance from the pressure regulating sylphon and the suit. This was done to provide a longer air line between suit and valve to dampen oscillations and to place the sylphon far enough from the valve that it more nearly measured suit pressure and not higher valve pressure. As a result, it was expected that the sylphon would allow the circuit to remain closed until suit pressure reached the desired value, thus allowing more rapid inflation. Figure 43 presents a photograph diagram of the valve, Model P-321-13; Figure 44 presents similar views of the pressure regulator, Model P-321-14. The pressure regulator is analogous in function to the pressure regulating component of Model P-321-11 described above, except that the sylphon applies its force through a lever whose fulcrum can be shifted to provide for adjustment of the pressure delivered. The valve is a four-way selector valve of the poppet type. When the solenoid is un-energized, air is passed out the exhaust or tank port to be led overboard or fed to the auxiliary fuel tank system. The suit is connected to ambient air through the suit exhaust port. When the solenoid is energized, the tank and suit exhaust ports are closed and air passes to the suit. The general principle of operation remains the same as with Model P-321-11.

5. In tests carried out by Lamport and Herrington at the University of Southern California Aero Medical Laboratory[55] the following results were obtained:

a. The subjects could not feel pulsation in the G suit despite

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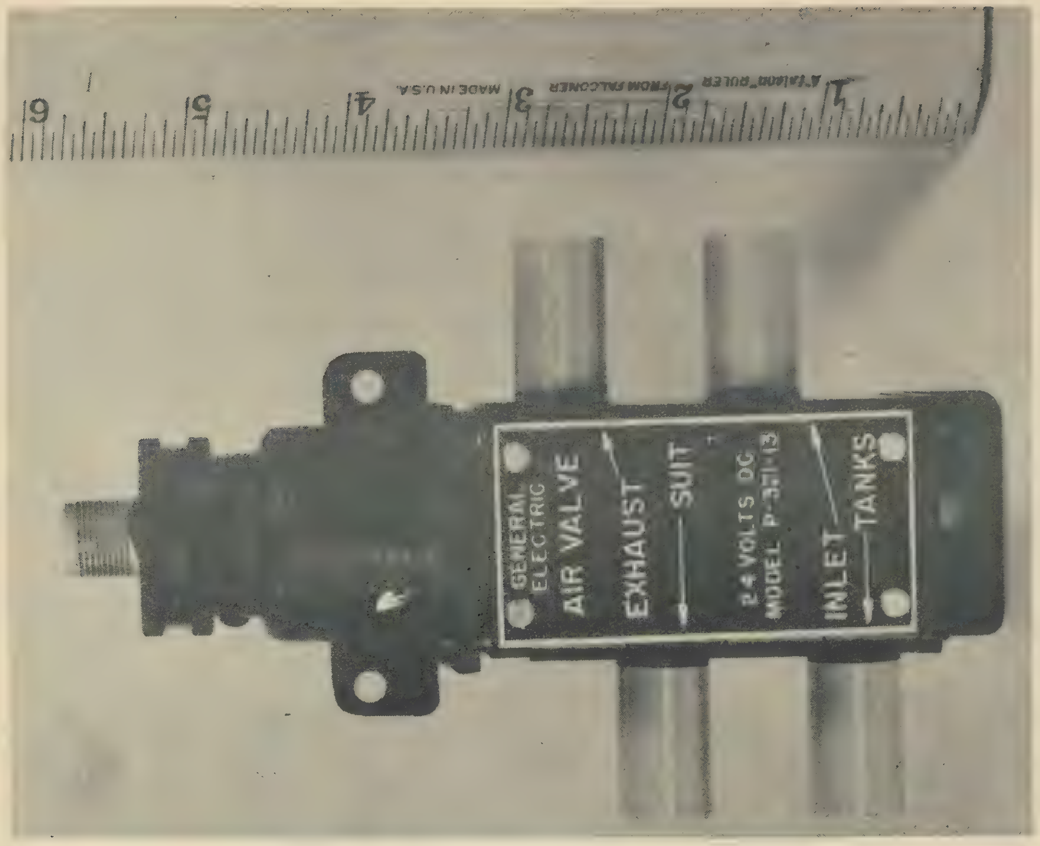
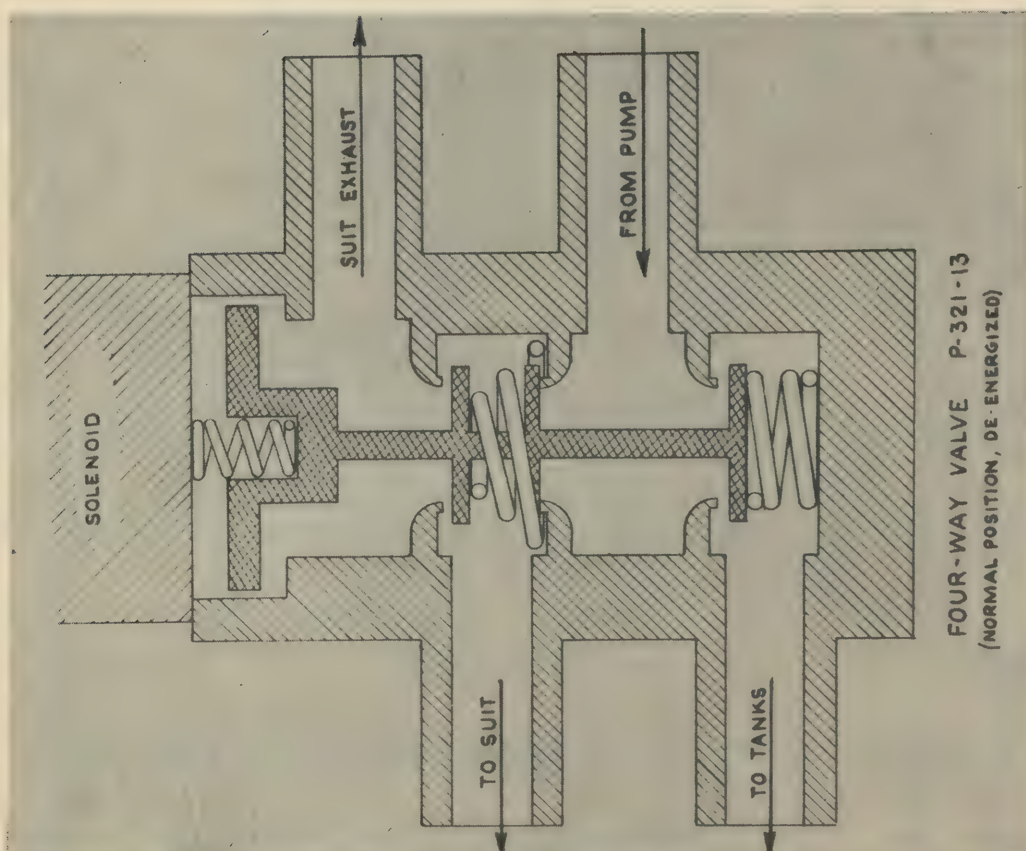
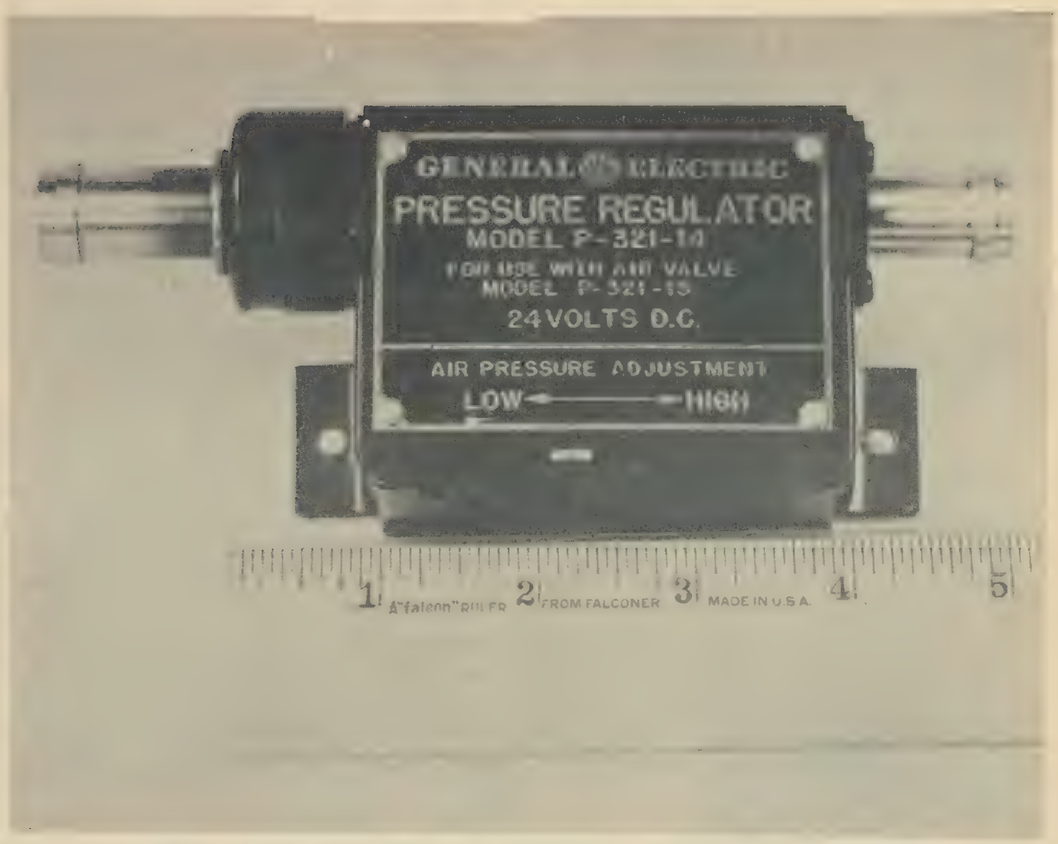
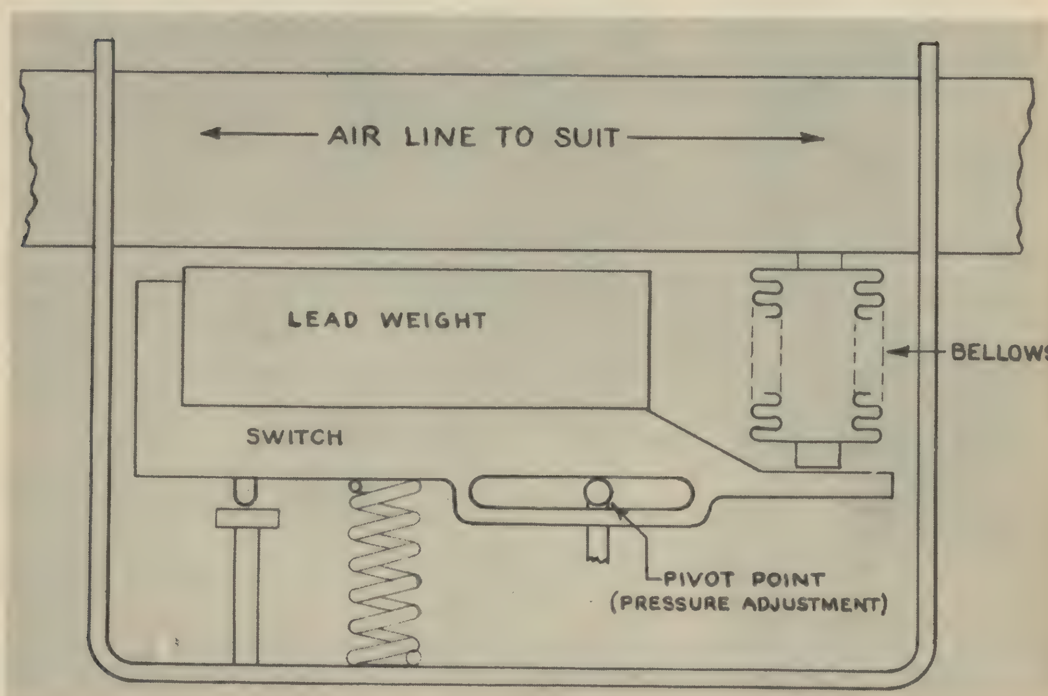




FOUR-WAY VALVE P-321-13
(NORMAL POSITION, DE-ENERGIZED)

FIGURE 43





PRESSURE REGULATOR P-321-14

FIGURE 44

measurable oscillations in suit pressure, (valve and regulator were separated by eight feet of hose).

b. Inflation time was rapid. One graph shows a G-4 suit inflated to 4.2 p.s.i. at 5.5 G in 1.5 to 2.0 seconds, another shows Model 12 PLS inflated to 11.2 p.s.i. at 5.1 G in 3-1/2 seconds.

c. The pressure rate per G delivered by the valve can be adjusted without altering the G at which the valve trips.

6. The data presented in the preceding paragraphs demonstrate that the principle employed in these valves is sound. Both valves employed poppets which are advantageous because the possibility of sticking as a result of the presence of extraneous matter is minimized. Apparently the objectionable, sensible oscillations in suit pressure and slow filling noted in the earlier model was successfully eliminated in the later one. The adjustable feature is most attractive. However, the requirement of an electrical circuit and source with their inevitible complications is a disadvantage particularly in the face of the fact that there exist adequate forces associated with accelerations to do the required work of operating the valve mechanically. Because of these considerations and the existence of mechanically actuated valves the General Electric valve and control have not yet been given aircraft tests by the USAAF.

D. <u>The weighted poppet type G compensated relief valve.</u>

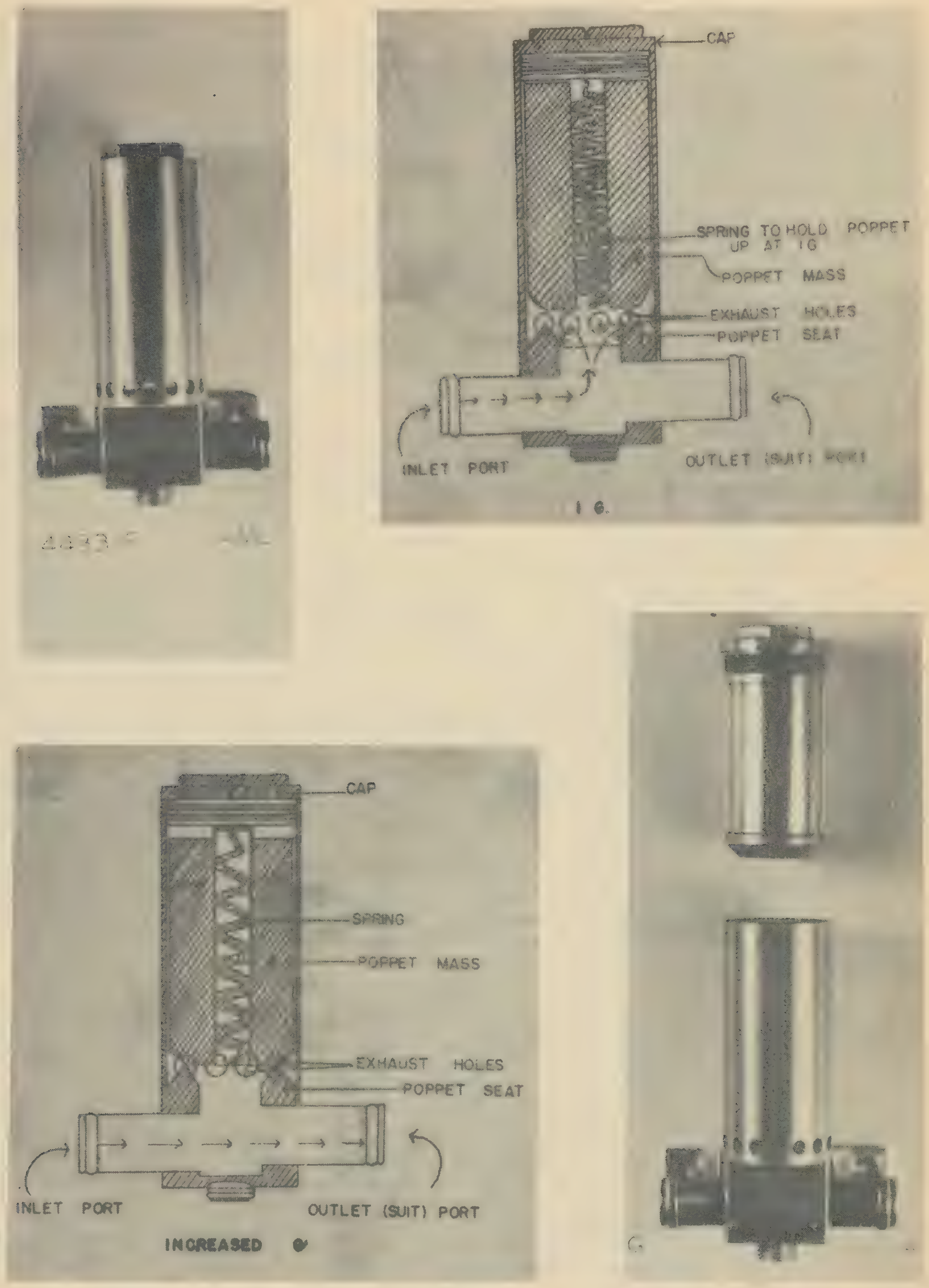
1. One of the simplest means of providing air pressure with a certain pressure increment per G is the use of the G compensated relief valve. A model, designed by Dr. E. H. Wood and Mr. Richard Cornelius (personal communication from Dr. Wood) is shown in photograph and schematic diagram in Figure 45. The poppet, a metal mass with a seating surface, is held up by an internal spring until a given G level is reached. During increased G, the weighted poppet seats, closing the exhaust holes and directing all air to the suit. When air pressure in the chamber below the poppet is great enough to raise it, the poppet lifts and opens the way for air to escape through the exhaust holes. The acceleration at which the poppet closes depends on the relationship between the mass of the poppet and the strength of the spring. The pressure increment per G varies directly with the mass of the poppet and inversely with its end area thus:

$$\Delta P \text{ per } G = \frac{W}{S}$$

Where W = weight of the poppet at 1 G

S = the end area of the piston

2. This simple valve functions well when used with a compressor which operates only during increased G. If it is used with a continuously running pump, a stop-cock valve, activated by acceleration, must be interposed between



CORNELIUS G COMPENSATED WEIGHTED POPPET RELIEF VALVE

FIGURE 45

the valve and the pump to prevent the suit from being inflated to low pressures at 1 G. It is probable that this feature could be eliminated by the use of a Venturi tube at the inlet port in an arrangement similar to that used in the General Electric valve P-321-11. A sketch of this modification, proposed by E. H. Wood, is presented in Figure 46.[35]

3. As long as pressurization of the auxiliary fuel tanks is required of the G valve, this simple unit is inadequate and complexities must be introduced to completely separate suit and exhaust ports at 1 G.

E. The three pressure valve (AAF type G-1) for the gradient pressure suit (AAF type G-1).

1. The G-1 suit demanded that air be delivered at three pressures, each increasing with G. The G-1 valve (Figure 47) designed by the Berger Brothers Company to meet these requirements, consists of a G activated, spring loaded, poppet type control valve which functions to divert all inlet air to the exhaust manifold until 1.5 G is reached and to direct inlet air to the three pressure regulating valves at accelerations greater than 1.5 G.[7] The three pressure regulating valves are identical in principle to the pressure regulating part of the M-2 valve which will be described below (Figure 51). Output air from each of the three pressure regulating valves is led to the quick detachable fitting cup, a female unit which mates with the male fitting attached to the G-1 suit. A seeker in the disconnect fitting insures that the suit is properly attached to the pressure leads from the valve. The disconnect fitting on the valve can be removed and placed remote from the valve where lack of space in the cockpit makes it necessary. The valve is 11 inches long and weighs 6-1/4 pounds. Air for the valve is furnished by the vacuum instrument pump. In the G-1 assembly air from the B-12 oil separator in the plane was led to a highly efficient oil separator, provided by the Berger Brothers Company, which removed residual oil. This added separator was used to protect the gum rubber bladders of the G-1 suit from oil vapor. From the second oil separator, air entered the G-1 valve.

2. The theoretical pressures to be delivered by the G-1 valve are 1.25, 1.13 and 1.0 p.s.i. per G when the valve is set to deliver 1.0, 0.75 and 0.5 p.s.i. if the control valve is manually closed at 1 G (Figure 10). The performance of eight valves, taken at random from a group submitted for test purposes, was observed on the ATSC centrifuge. Results are presented in Figure 48. The eight valves performed in a uniform manner. Suit pressures increased nearly linearly with the G at a rate of approximately 1 p.s.i. per G. The difference between high and intermediate pressures was only 0.2 to 0.3 p.s.i. at any observed G level. The "low pressure" remained approximately 1 p.s.i. less than the high pressure throughout.

3. The need for pressurizing auxiliary fuel tanks from the vacuum instrument pump arose at the time the limited number of G-1 suits and valves which saw service in the Eighth Air Force were delivered. This emergency was met by the introduction of a Cornelius G activated stop-cock valve into the system between the oil separator and the G-1 valve. This stop-cock valve

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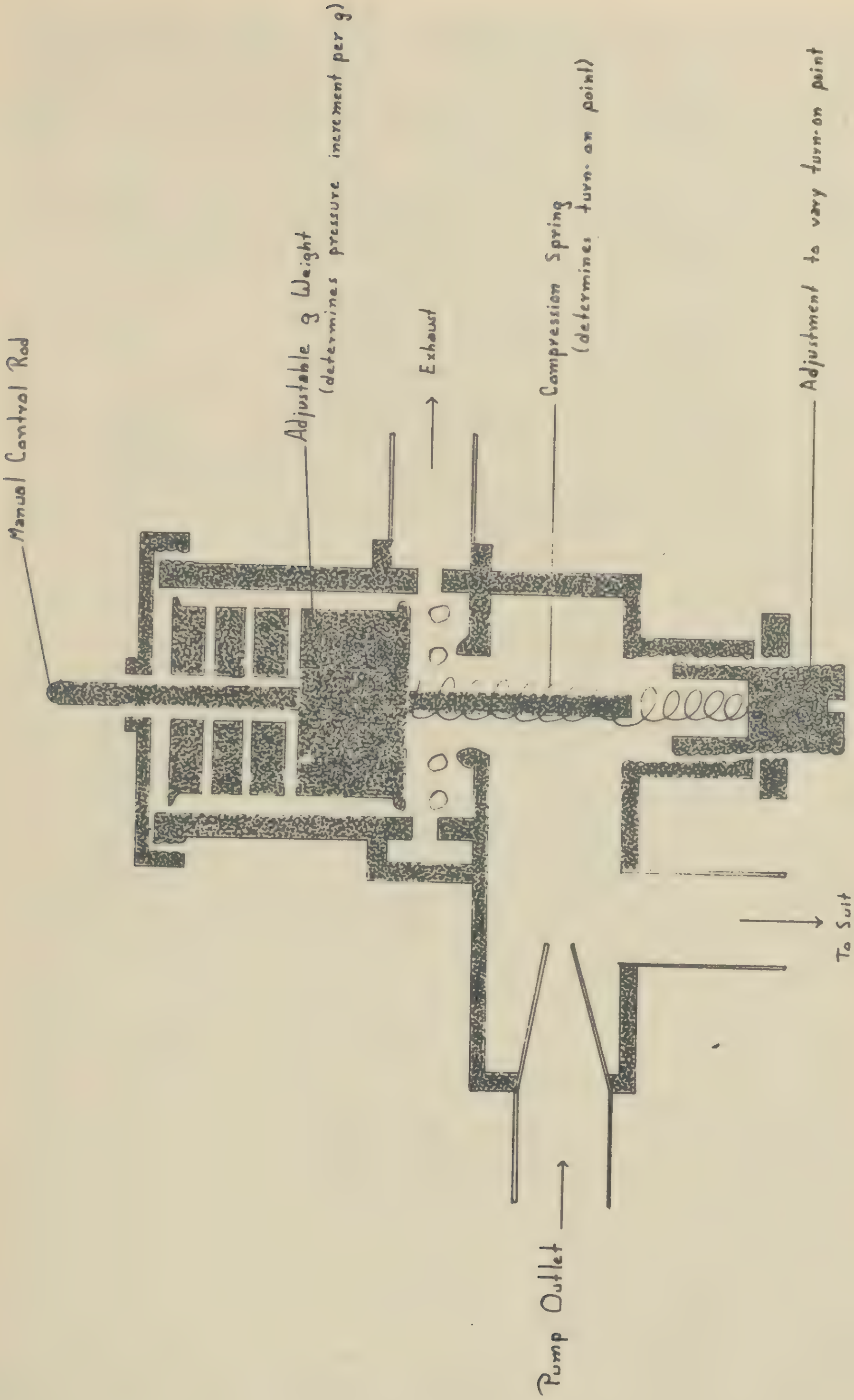
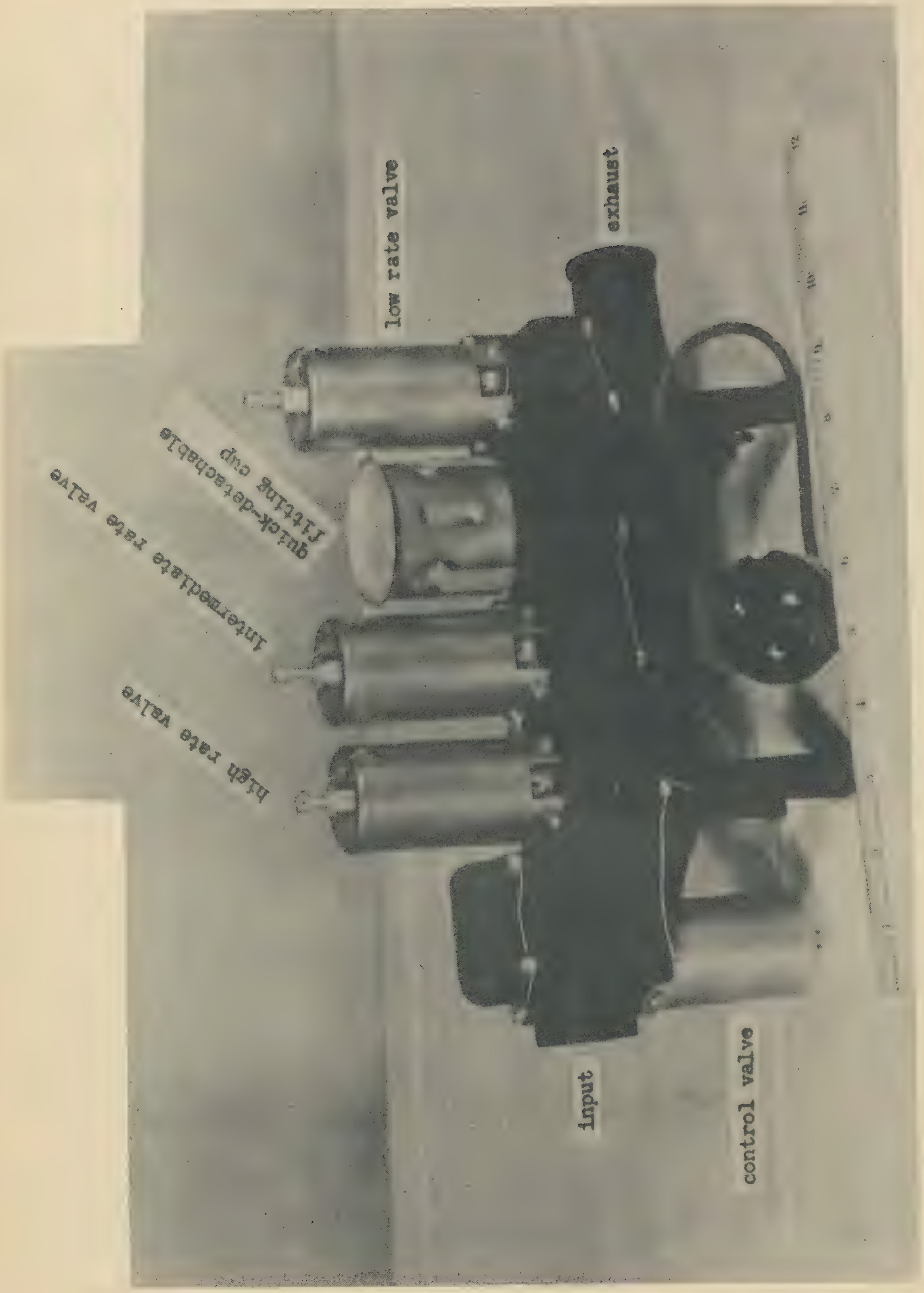


Schematic Diagram of an Adjustable Single Unit Valve Incorporating the G-E Venturi Action at the Suit Inlet

Mayo Aero Medical Unit
Date 11/2/45 By EHW/MC

FIGURE 46



AAF TYPE G-1 VALVE

FIGURE 47

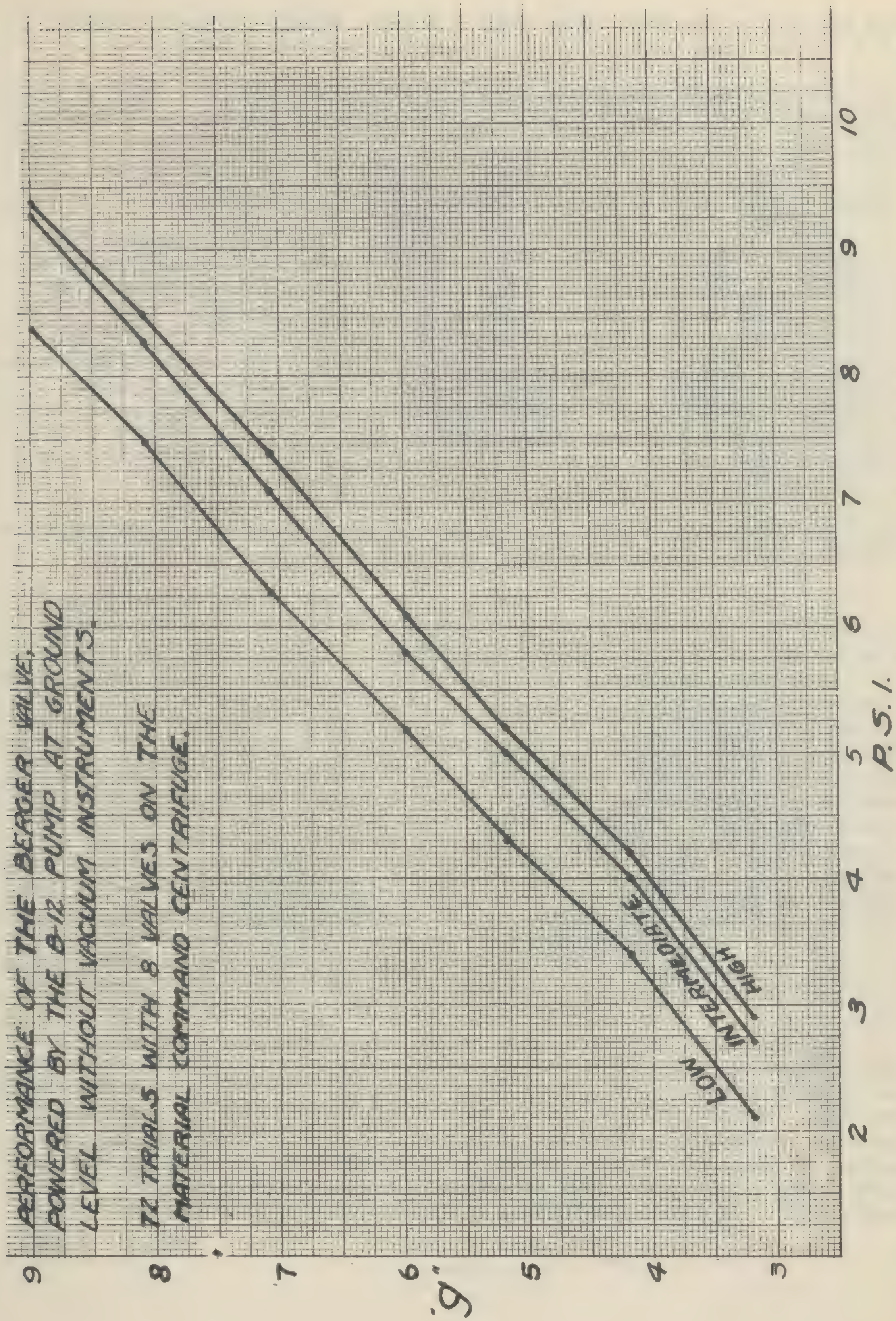

PERFORMANCE OF THE BERGER VALVE, POWERED BY THE B-12 PUMP AT GROUND LEVEL WITHOUT VACUUM INSTRUMENTS.
72 TRIALS WITH 8 VALVES ON THE MATERIAL COMMAND CENTRIFUGE.
LOW
INTERMEDIATE
HIGH
"g"
P.S.I.
2
3
4
5
6
7
8
9
10

FIGURE 48

deviated all air to the fuel tanks until 2 G was reached. At accelerations above 2 G all the pump output air was directed to the G-1 valve.

4. The discovery that single pressure suits were equally effective as suits with multiple pressures rendered the G-1 valve with its accoutrements obsolete.

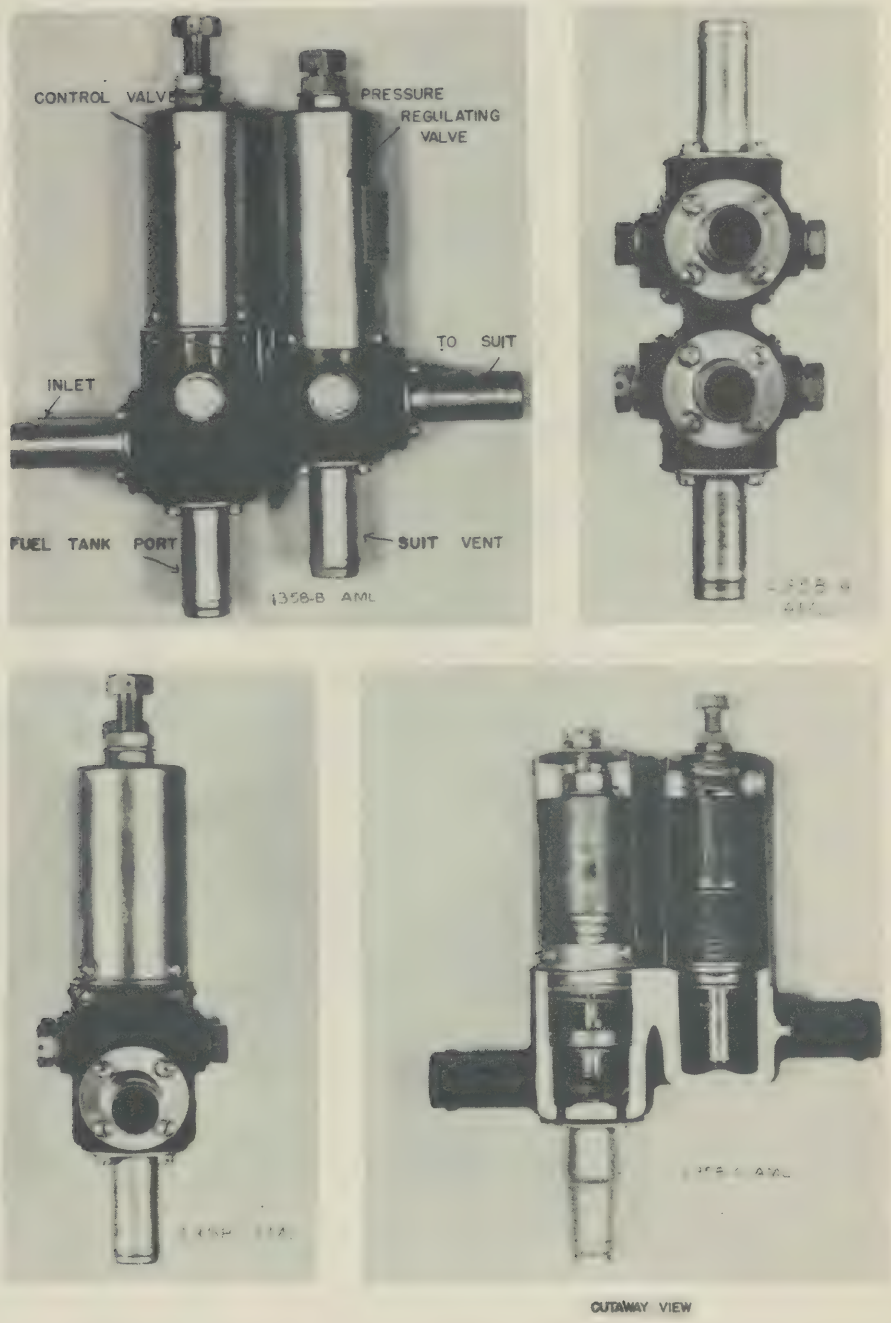
F. The AAF type M-2 valve (G-2 valve, Berger single pressure valve).

1. In January 1944 when the AAF changed from the triple pressure G-1 suit to the single pressure G-2 suit a valve was needed which would pressurize the G suit at a single pressure of 1 p.s.i. per G and adequately pressurize the auxiliary fuel tanks as well. Military requirements demanded that a valve combining these functions be developed quickly. The G-2 valve was designed by Mr. Roy Versoy and Mr. Fred Moller of the Berger Brothers Company, New Haven, Connecticut, to serve these purposes. When this valve was standardized it became the AAF type M-2 valve. Specifications exist for a M-1 and a M-3 valve. These differ from the M-2 valve only in the masses of the compensatory weight which cause the M-1 and M-3 valves to deliver 0.8 and 1.3 p.s.i. per G respectively. Neither the M-1 or the M-3 valve was ever procured for use.

2. The M-2 valve (Figures 49, 50 and 51) consists of two connected valve units, the control valve and the pressure regulating valve.

a. The control valve. The function of the control valve is to direct air to the tank port in level flight, and to the pressure regulating valve during maneuvers which produce positive G. It is a three way, spring loaded, G activated, weighted poppet type valve. At accelerations smaller than that required to trip the valve the control valve stem and weight are held in the up position by the control valve spring. The control valve poppet head is seated above and air entering the inlet port passes out the tank port to be led overboard or to pressurize the auxiliary fuel tank system (Figure 50). At accelerations great enough to trip the valve, the combined weight of the control valve stem and superimposed weight is sufficient to overcome the control valve spring and cause the valve system to move downward, unseating the poppet above and seating it below. Air is then directed through the upper poppet seat to the pressure regulating valve (Figure 51). If the tank port is vented to ambient air, the control valve trips at 2.75 G. If auxiliary tanks are being pressurized to 4 to 5 p.s.i., this pressure, acting upward against the area of the upper poppet seat, lends support to the control valve spring and raises the acceleration required to trip the control valve to approximately 4 G.

b. The pressure regulating valve. The function of the pressure regulating valve is to meter air to the G suit at a rate of approximately 1 p.s.i. per G. This is accomplished by variation in the size of the valve vent orifice (Figure 51). The size of this vent orifice is determined by the position of the pressure regulating valve stem. The position of this stem, in turn, is determined by the forces acting upward and downward upon it. During increased positive G, the effective weight of the valve spring and superimposed weight, increasing with the G and aided slightly by the low rate pressure regulating



M-2 PRESSURE REGULATING VALVE
FIGURE 49

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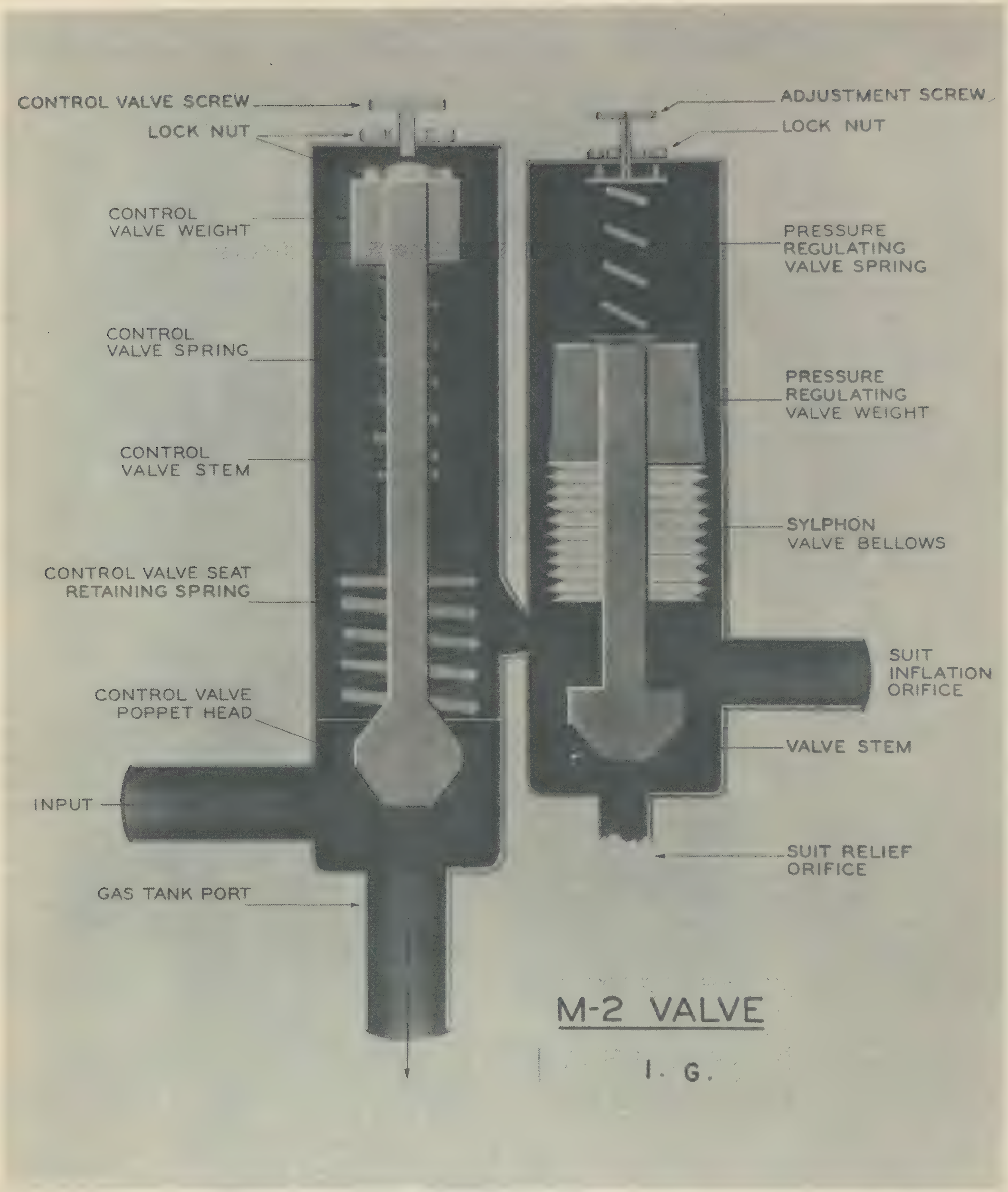
CONTROL VALVE SCREW
LOCK NUT
CONTROL VALVE WEIGHT
CONTROL VALVE SPRING
CONTROL VALVE STEM
CONTROL VALVE SEAT RETAINING SPRING
CONTROL VALVE POPPET HEAD
INPUT
GAS TANK PORT
ADJUSTMENT SCREW
LOCK NUT
PRESSURE REGULATING VALVE SPRING
PRESSURE REGULATING VALVE WEIGHT
SYLPHON VALVE BELLOWS
SUIT INFLATION ORIFICE
VALVE STEM
SUIT RELIEF ORIFICE
M-2 VALVE
I. G.

FIGURE 50

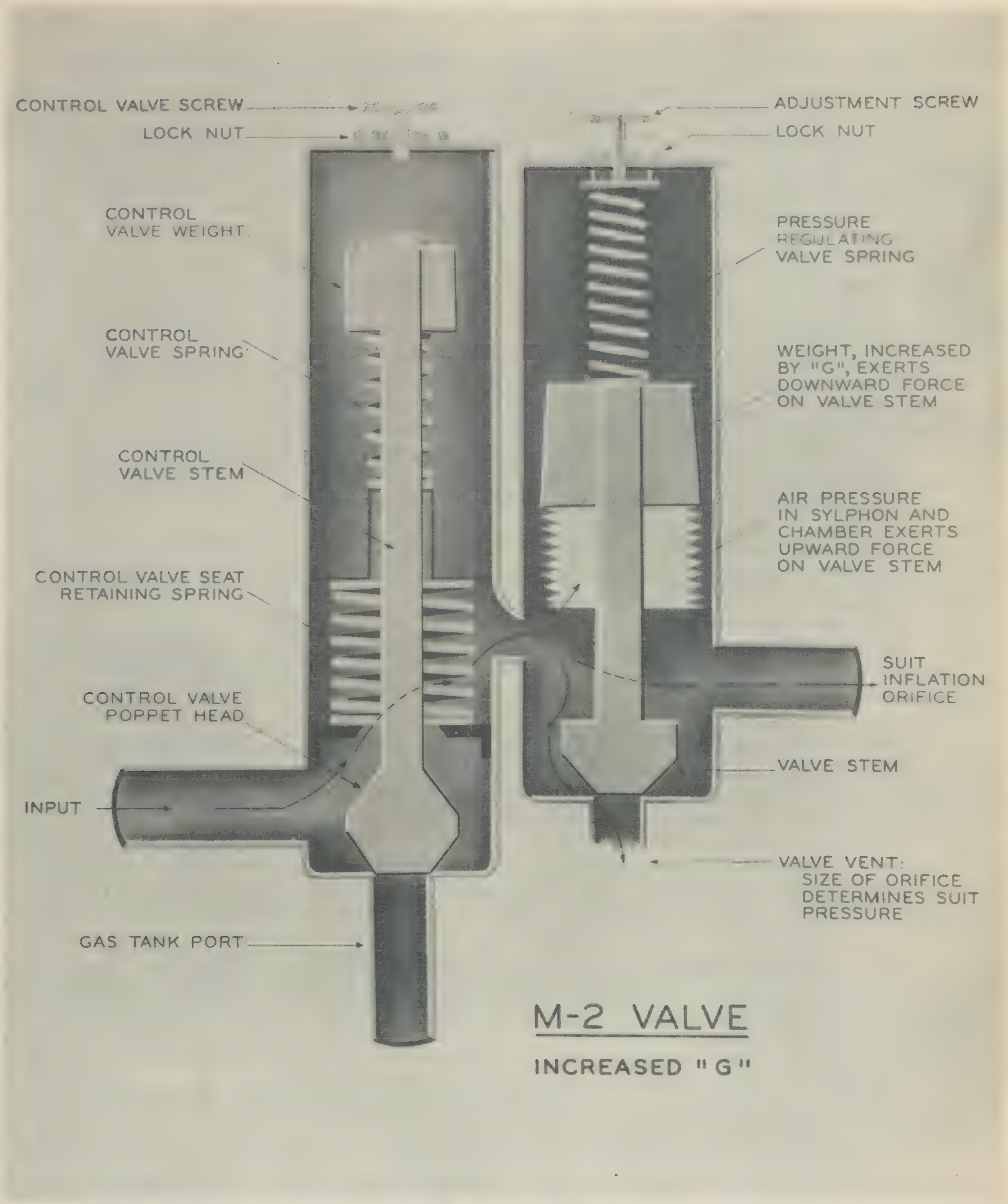
CONTROL VALVE SCREW
LOCK NUT
CONTROL VALVE WEIGHT
CONTROL VALVE SPRING
CONTROL VALVE STEM
CONTROL VALVE SEAT RETAINING SPRING
CONTROL VALVE POPPET HEAD
INPUT
GAS TANK PORT
ADJUSTMENT SCREW
LOCK NUT
PRESSURE REGULATING VALVE SPRING
WEIGHT, INCREASED BY "G", EXERTS DOWNWARD FORCE ON VALVE STEM
AIR PRESSURE IN SYLPHON AND CHAMBER EXERTS UPWARD FORCE ON VALVE STEM
SUIT INFLATION ORIFICE
VALVE STEM
VALVE VENT: SIZE OF ORIFICE DETERMINES SUIT PRESSURE
M-2 VALVE
INCREASED "G"

FIGURE 51

valve spring, acts to depress the stem and close the vent. At the same time, air pressure within the sylphon acting upwards, against the lower surface of the pressure regulating valve weight, acts to raise the stem and open the vent. The balance between these forces determines stem position and orifice size at a given moment. The pressure required to vent the valve, therefore, increases with the G. The vent orifice serves to empty the suit when the episode of increased G has passed and the control valve has closed.

3. Changes in the G-2 valve occasioned by experienced gained in service usage.[8] When the G-2 valve, prototype of the M-2 valve, was first used in the P-51 aircraft it was mounted to a bracket attached to the after cooling housing of the engine. The Eighth Air Force reported several failures of the valve in this aircraft, undoubtedly caused for the most part by the excessive vibration to which the valve was subjected when it was mounted in this position. No similar failures were reported in other aircraft (P-47 and P-38) in which the valve was not mounted on the engine. The valve was moved to a different location in the P-51, a change which could be expected to correct the difficulty. It was felt, however, that the experience in the Eighth Air Force indicated potential weaknesses in the valve which should be corrected. Chief among these were:

a. Lead weights, which had come loose from the valve stems, were changed to brass.

b. Valve stem guides, formerly made in two pieces soldered together, were made of one piece to increase their accuracy and hence the accuracy of seating of the valve stems themselves.

c. Stop screws in the caps on the valve units had been made of brass. Vibration caused some of them to come loose due to wearing of the threads. These screws were changed to steel and tapped steel inserts were provided in the brass caps to receive them.

d. Since the sylphons were the best obtainable, no change in them was made despite the fact that some had cracked. It was anticipated that removal of the valve from the engine would correct the trouble.

e. A new diecast body was made which allowed all nipples to be separate parts attached to tapped bosses. In this way the formerly oversized nipples at the inlet and suit ports were replaced by proper sized nipples for a 5/8 inch hose connection.

f. The acceleration at which the valve tripped was raised from 2 G to 2.75 G in response to requests from various air forces.

g. A nipple was placed on the suit vent port so that this port could be led by tubing to an area where pressure was similar to cockpit pressure. This measure will prevent the annoying suit pressurization in level flight which results if the suit vent port of the valve opens into an area where pressure is greater or markedly less than cockpit pressure.

4. These changes are incorporated into the M-2 valve.

5. Performance of the M-2 valve.

a. Suit pressure versus G in static tests. The M-2 valve, like other G valves, is tested statically by addition of weights to the control and pressure regulating units to simulate acceleration while suit pressure is measured with a pressure gauge. A test kit is available which contains the proper weights and gauge. As is the case with many other types of G valves, chattering may occur if a G suit is not attached to the valve as an air reservoir to dampen pressure oscillations. Results of such tests show that suit pressures increase at a rate of approximately 1 p.s.i. per G when air flow through the valve is held constant. Pressure at a given G level varies with air flow through the valve. In the case of one valve, suit pressure varied from 2.5 to 7.25 inches mercury (1.2 to 3.6 p.s.i.) at 2 G and from 15.75 to 19.25 inches mercury (7.7 to 9.5 p.s.i.) at 8 G when air flow at each G varied from 5 to 30 c.f.m. (Figure 52). If air flow through the valve is constant, suction applied to the suit vent port reduces suit pressure at a given G value. When the suit vent port pressure was varied from ambient to 150 mm. Hg suit pressures at given G levels varied over a range of approximately 1 p.s.i. (Figure 52).

b. Comparison of results in static tests, centrifuge tests and aircraft tests. Static and centrifuge tests of the M-2 valve yield uniform results if air flows are comparable. Suit pressures delivered by the valve in P-51 and P-47 airplanes were measured in tests at Eglin Field in June and July 1944 and later in an A-24 airplane at Rochester, Minnesota.[40] In all cases, suit pressure delivered in the airplane was approximately 1 p.s.i. less at a given G level than that obtained in static and centrifuge tests. Though the air flows used in the various cases were not recorded, it is presumed that the usual values of 15 to 20 c.f.m. were used in the static and centrifuge tests. If the aircraft tests were carried out at altitudes of 15,000 to 20,000 feet where the volume output of the vacuum instrument pump declines, at least part of the discrepancy might have resulted from differences in air flow in the two cases. Indeed, as Wood points out, a marked lessening of the suit pressure in the A-24 airplane was found to result from inability of the valve to maintain required pressures from very low volume output pump with which this airplane was equipped at the time.

c. Continuous pressurization of the suit in level flight. Since the suit vent port of any G valve necessarily communicates with the suit in level flight, the suit will inflate continuously if the suit vent port of the valve vents into an area in which pressure is greater than cockpit pressure surrounding the suit. The magnitude of the suit pressure under these conditions will be that of the pressure differential between the two areas. Moreover, in the case of the M-2 valve, a negative pressure of 25 mm. mercury or more at the suit vent port results in slight suit pressurization in level flight. Air in a G suit at a pressure as low as 5 mm. mercury is annoying to the wearer over a period of time. Continuous pressurization has not proved to be a problem in P-51 or P-38 aircraft, though the suit vent port of the valve vents into the accessories compartment ahead of the firewall. In the P-47 this ready pressure, as it has been called, has been troublesome. When either the Clark-Cornelius valve (see below) or the M-2 valve was mounted in the accessories compartment suit pressure in level flight was found to increase with indicated air speed from 0.1 p.s.i. (5 mm. mercury) at 200 m.p.h. to 0.6 p.s.i. (30 mm. mercury) at 360 m.p.h. The fact that the same pressures were obtained when a line connected to the suit was allowed to vent directly into the accessories compartment

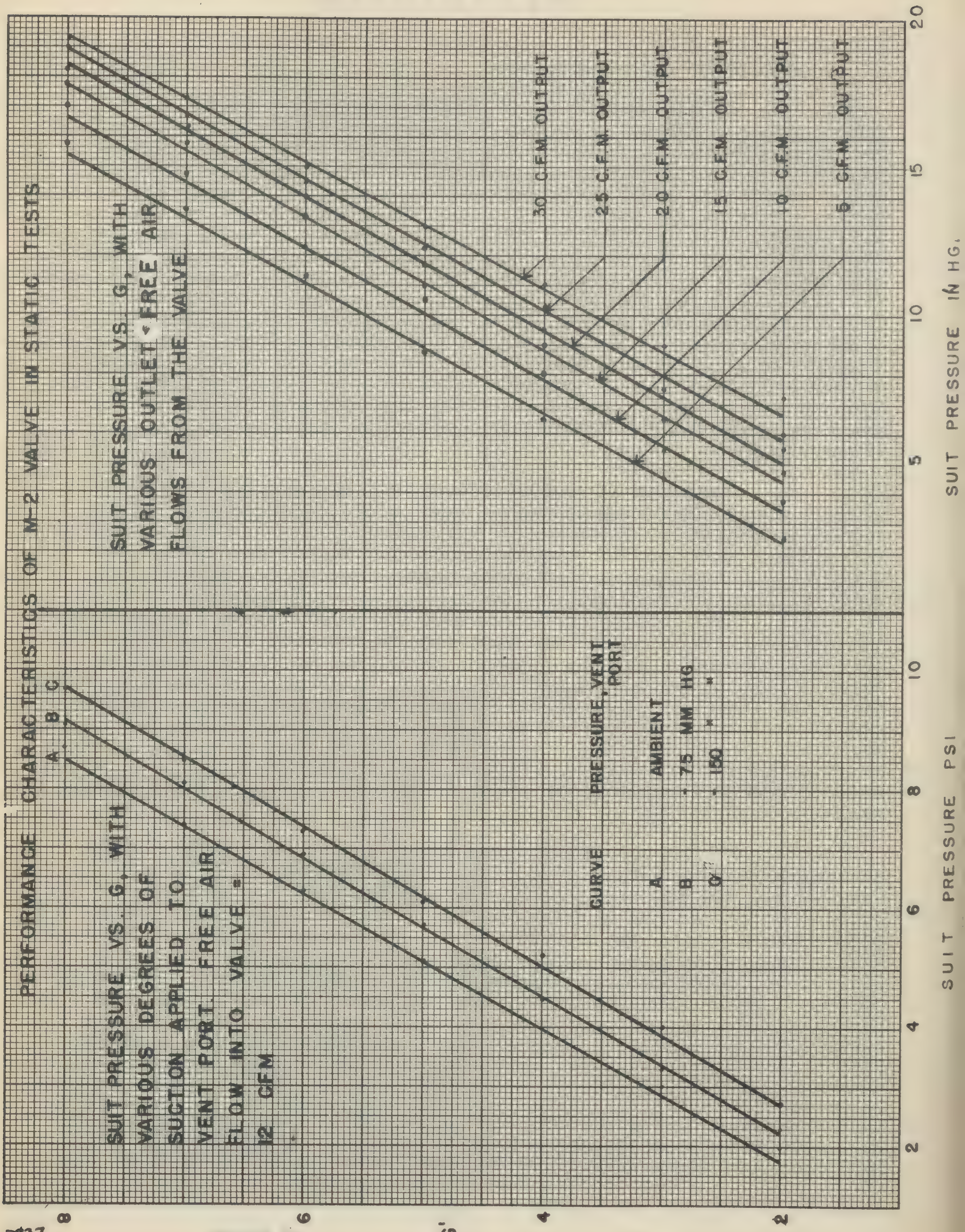

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FIGURE 52

with no G valve in the system demonstrates that the suit pressure is the result of a greater pressure in the accessories compartment than in the cockpit.[40] The installation specification for the M-2 valve (AAF Specification No. R-40982) specifies that the valve be placed in the accessories compartment. This choice was made both to eliminate the double air line which would be necessary between accessories compartment and cockpit to lead air to the valve and from the valve to the auxiliary fuel tank pressure line if the valve were in the cockpit and to eliminate venting of the air from the valve into the cockpit during increased positive G. The latter might be objectional because of the possibility of oil vapor and carbon monoxide in the air. If the suction relief valve for the vacuum instrument pump were placed in the cockpit in all AAF fighter planes, as it is said to be in the Navy Air Forces, the instrument pump output air would, in the final analysis, be cockpit air. Some AAF airplanes have this suction relief valve in the accessories compartment where contamination with carbon monoxide could occur. Efforts have been made to eliminate ready pressure in the P-47 by venting the suit vent port of the M-2 valve into the wing root. Early reports from the ETO indicated that the method was successful but later reports have indicated that the problem still exists.

d. If the M-2 valve is subjected to inlet air flows in excess of 45 c.f.m. air pressure in the control valve chamber becomes great enough that it can overcome the spring which returns the control valve to the 1 G position after an episode of increased G by acting on an unbalanced area in the lower poppet. When this happens, the suit continues to be inflated after a return to 1 G. This will occasionally occur if the M-2 valve is used in jet propelled airplanes.

5. It was demonstrated at the AAF Proving Ground Command, Eglin Field, that the additional oil vapor separator used in the G-1 pump-valve assembly was unnecessary since no oil vapor entered the suit bladders if only the standard B-12 separator in the airplane was used.[68] Even after continued use and although the valve may contain oil, the suit remains oil free. As a result, the extra oil separator was abandoned.

G. The Clark-Cornelius valve (US Navy C-C-1 valve).

1. The Clark-Cornelius valve is the standard US Navy G valve and has been used to a limited extent by the US Army Air Forces. It was designed by Mr. Richard Cornelius, of the Cornelius Company, Minneapolis, Minnesota, and modified and manufactured by the David Clark Company, Worcester, Massachusetts. It is designed to receive air from a pump, to pressurize the G suit during increased positive G, and to pressurize the auxiliary fuel tank system when this function is required.

2. General principles of operation. The course of air flow through the valve is governed by the position of the grooved piston within the valve body (Figure 53). Thus the valve is a selection valve which can direct air either to the tank port or to the suit port or to both ports.

3. Details of function.[10]

a. Air from the pressure source enters the valve through the inlet port. At G values of plus 1.75 G or less, the coiled spring within the piston

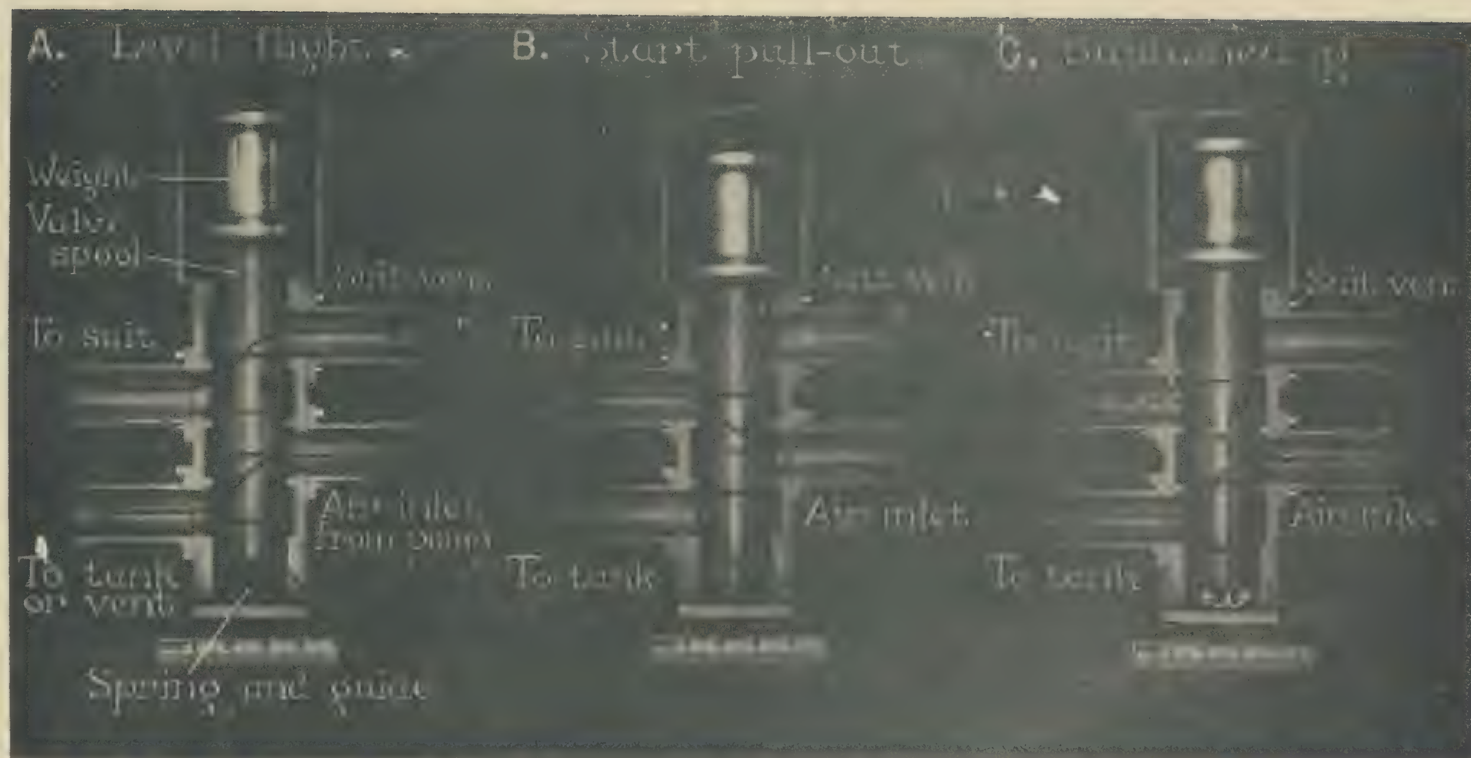


FIGURE 53 - CUTAWAY VIEWS OF CLARK-CORNELIUS VALVE

4536 G. A M L

supports the piston and superimposed weight in the raised position. With the piston fully up, air is directed out the tank port of the valve (Figure 53A).

b. At accelerations of 1.75 G and greater, the combined weight of the piston and superimposed weight is sufficient to overcome the coiled spring and the piston moves downward. When it is fully down all air from the pressure source is diverted to the suit port (Figure 53B).

c. When this occurs, air under pressure also enters the holes at the level of the upper groove of the piston and flows through a passage drilled through the long axis of the piston to pressurize the chamber beneath it (Figures 53B and 53C). Force from air pressure in this chamber, acting upward against the bottom surface of the piston, is not counterbalanced by any similar force from air pressure acting in the opposite direction. Accordingly, when the force in this chamber, acting on the end area of the piston, aided slightly by the spring, is great enough to slightly exceed the downward acting force, consisting of the total compensatory weight (piston and superimposed weight) multiplied by the G, the piston rises. It can reach a position at which the chamber of the valve which leads to the suit port is isolated from both suit vent and tank ports, and air flows from inlet to tank ports as it does at 1 G. In actual use the piston probably hunts near a position such as that shown in Figure 53C in which most of the input air goes to the tanks but enough goes to the suit port to replace that lost through leakage from the system. Thus the valve is both G activated and G compensated since both the downward movement of the piston and the pressure required to raise it to the intermediate position depend on the G.

d. After the episode of increased G has passed the piston returns to its original position, thereby allowing the air in the G suit to escape through the suit vent port (Figure 53A).

e. The pressure increment per G at which air is delivered to the suit varies directly with the magnitude of the total compensating weight (piston and superimposed weight) which must be lifted by air pressure to deny admission of further air to the suit and inversely with the end area of the piston against which this pressure works. Therefore:

$$\triangle P \text{ per } G = \frac{W}{S}$$

Where $\triangle P$ per G = pressure increment per G

S = end area of the piston

The standard Clark-Cornelius valve piston weighs 50 grams and the additional weight 182 grams. The total compensating weight is then 232 grams, or 0.51 pounds. Piston end area is 0.5095 square inches. Therefore:

$$\frac{\triangle P}{G} = \frac{0.51}{0.5095} = 1 \text{ p.s.i./G, beginning}$$

at the G at which the valve begins to pressurize the suit.

f. The G at which the valve begins to pressurize the suit is determined by the strength of the coiled spring which must be overcome before the piston moves downward. In the standard Clark-Cornelius valve this spring permits downward movement of the piston at between 1.5 and 2.0 G. Because the piston is balanced with respect to tank and inlet pressure, variations in tank port pressure which accompany pressurization of auxiliary fuel tanks do not affect the tripping of the valve.

4. Performance of the Clark-Cornelius valve.

a. Suit pressure delivered by the valve is the same in static, centrifuge, and airplane tests.[40]

b. In static tests the valve delivers the same suit pressure at any given G when air flow varies from 5 to 30 c.f.m. (Figure 54).

c. The pressure drop from inlet through suit port when the piston is held fully down is shown in Figure 54.

H. <u>Modification of the Clark-Cornelius valve for use in jet propelled aircraft.</u>

1. General requirements for anti-G valves which receive air from the compressor of the jet engine.[10]

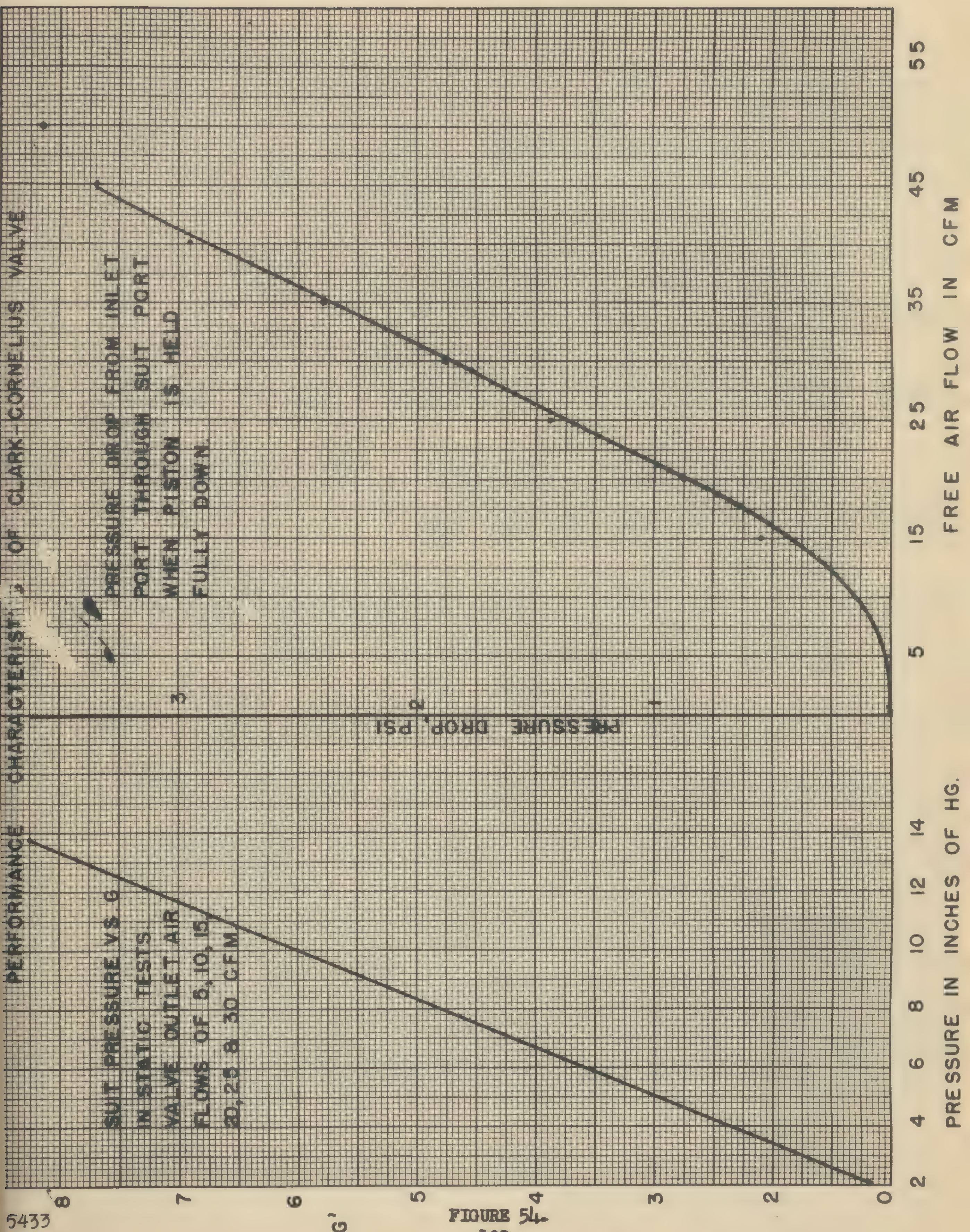
a. The anti-G valve must conserve air in level flight, since air loss means loss of thrust to the aircraft and lowering of operating efficiency. The ideal valve would pass no air except when pressurization of the suit was required.

b. The anti-G valve system must be able to meter air to the suit at the proper pressure and undergo no significant variation in the G at which suit pressurization begins, all in the face of input pressures ranging from 10 to 125 pounds per square inch gauge pressure. The latter figure, though much higher than input pressures likely to occur during ordinary operating conditions, might occur at low altitude if ground temperatures were very low.

2. The first efforts to adopt the Clark-Cornelius valve to jet propelled aircraft consisted in simply closing the tank port to prevent air flow at 1 G.[10] When this was done the following facts were noted:

a. Pressure regulation was satisfactory.

b. At 1 G some air leaks through the space between the piston and the lands of the valve body causing an air loss. Manufacturing tolerance allows pistons with diameters of 0.8105 to 0.8110 inches and bodies with diameters of 0.8125 to 0.8130 inches. Thus total tolerance can vary between 0.0025 and 0.0015 inches. Air loss varies slightly from valve to valve as shown in Figure 55. The curve of free air flow from the valve at 1 G versus input pressure is linear and shows a leak of 1.9 cubic feet per minute when input pressure is 20 pounds per square inch, and 7.2 cubic feet per minute when input pressure is 80 pounds per square inch. From consultation with General Electric Company engineers it was learned that this degree of air loss is acceptable.



5433

FIGURE 54.

c. With the tank port closed the pressure drop through the orifice leading to the suit vent port at 1 G is sufficient to result in small but appreciable suit pressures (Figure 55). The magnitude of this pressure varies with the number of suit vent ports, the presence or absence of a wire screen over a suit vent port and with rotation of the piston. The curves for suit pressure at 1 G versus inlet pressure in Figure 55 are average for two valves and indicate a suit pressure of 27.5 millimeters of mercury when the valves had one screened suit vent port and were subjected to an input pressure of 80 pounds per square inch. These data were collected when the piston was in one position. If the piston is rotated while kept in the one G position different figures can be obtained. The essential fact remains, however, that some air will accumulate in the suit in level flight if the valve is used in this manner. This fact was confirmed in aircraft tests in the YP-80.

d. When the valve was used without an air filter in the YP-80 malfunction occurred because small metal shards occasionally entered it and because a sludge-like substance believed to come from kerosene contamination collected on the lands.

e. It is theoretically possible although improbable that the piston could stick in the down position and allow the anti-G suit to receive air at the pressure discharge pressure. To prevent this hazard from occuring a relief valve is needed on the suit side of the anti-G valve.

3. From the above information it was concluded that a modification of the Clark-Cornelius valve suitable for use in jet propelled aircraft could be made. This modification must eliminate suit inflation in level flight, must include a pressure relief valve to prevent over-inflation of the suit in the event of malfunction of the valve and will require an air filter.

4. Modification of the Clark-Cornelius valve to render its operation satisfactory when the air source is the compressor of the jet engine.

a. The piston of the Clark-Cornelius valve has been modified to eliminate pressurization of the suit in level flight.[10] This piston, submitted by Mr. David Clark of the David Clark Company, Worcester, Massachusetts, has only one groove, placed at the location of the upper groove in the standard piston (Figure 56). The edges of this groove are chamfered. When the piston is used under the proper circumstances negative suit pressures are observed at 1 G. It is believed that the chamfered edges of the piston groove decrease the turbulence of air flow at the suit vent port lowering the pressure drop through this orifice and creating a Venturi effect. When the modified piston is used in a standard Clark-Cornelius valve body and the presence or absence of suit inflation at 1 G varies as the tank port is opened or closed. In a group of six valves tested with the tank port closed and the suit vent port either screened or unscreened all showed both positive and negative pressures at 1 G when input pressures varied from 0 to 80 pounds per square inch. Negative or positive pressures could be obtained at will by rotating the piston within the valve body. When both the suit vent port and the tank port were opened and screened with a flat 50 mesh screen five of the six valves showed negative suit

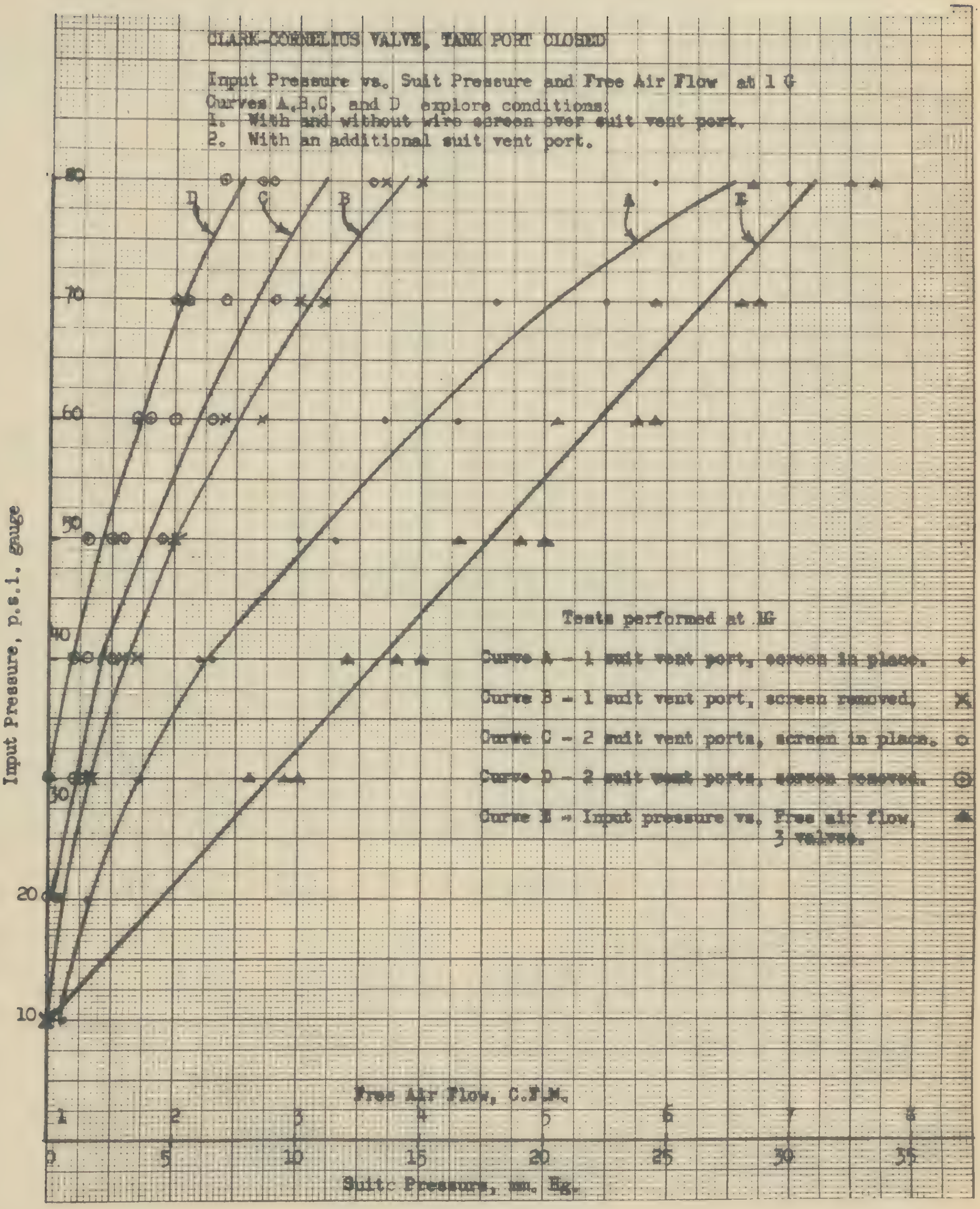
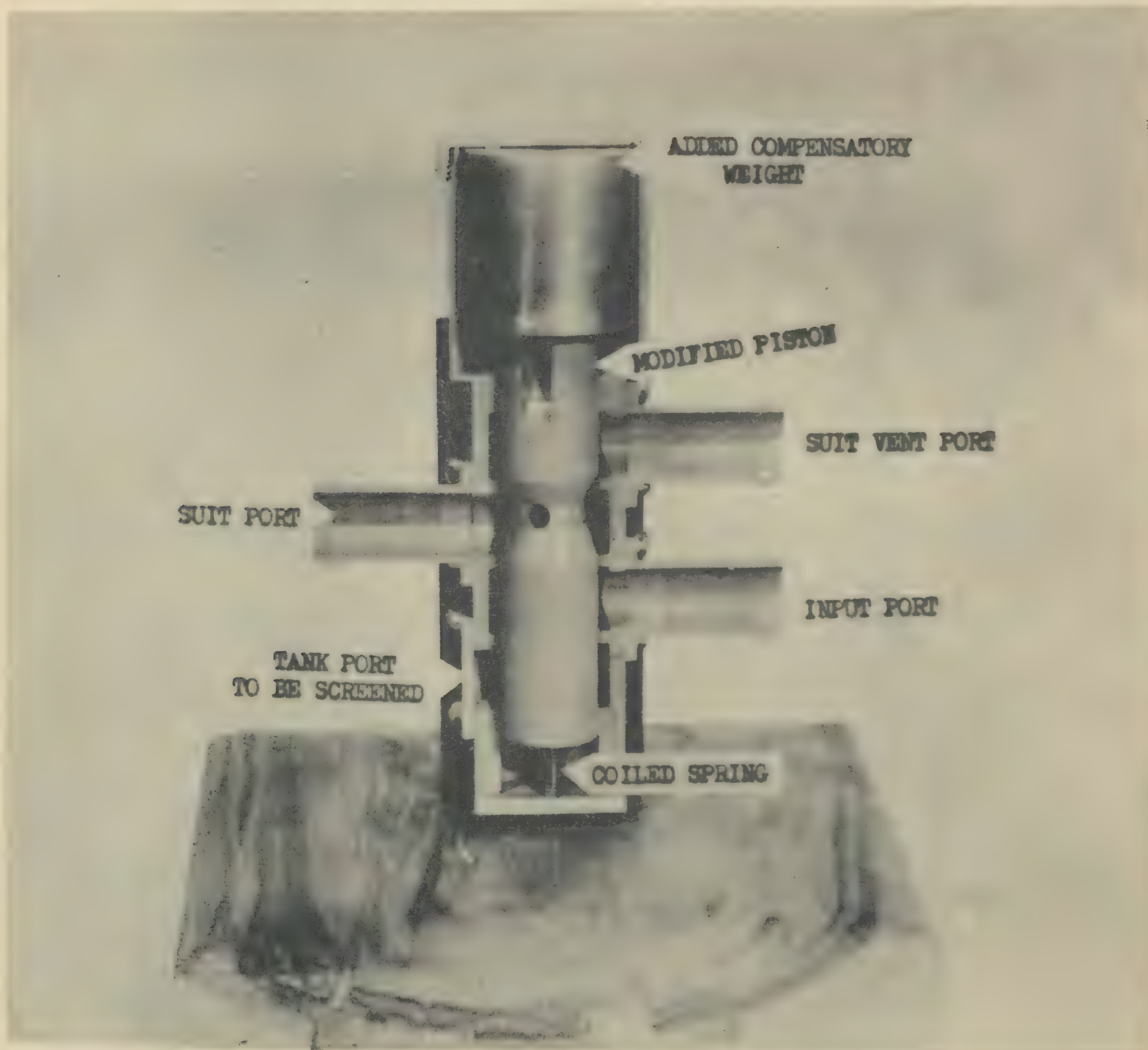


Figure 55

4528D-A M L



CUTAWAY VIEW OF WORKING PARTS OF CLARK CORNELIUS VALVE MODIFIED FOR USE IN JET PROPELLED AIRCRAFT

FIGURE 56

pressures at all times at 1 G. This negative pressure varied in magnitude from 0 to minus 350 centimeters of water. The sixth valve showed positive pressures with certain piston positions at input pressures above 50 pounds per square inch. Further study of this valve reveals that its air loss at 1 G, that is, the volume of air which has to be vented, was greater than was the case with the other five valves (see valve three, Table 2). It is concluded that the problem of suit inflation in level flight is eliminated by use of the modified piston in the standard Clark-Cornelius valve body with suit vent and tank ports screened.

b. Air loss at 1 G from the valve with the modified piston is the same as air loss from the standard Clark-Cornelius valve when both valves have tank ports closed. When the valve with the modified piston has its tank port open total air loss at 1 G is increased slightly. Data from six such valves are presented in Table 2.

c. The G at which the valve begins to pressurize the suit increases slightly with the input pressure. In tests in which the G to trip the valve was determined statically with the use of test weights the data presented in Table 3 were obtained. In trials on the centrifuge one such valve continued to trip at 1.5 to 2.0 G when input pressures were 50 pounds per square inch or less, and at variable but generally higher come-on points at input pressures of 100 and 125 pounds per square inch. Variations of this magnitude in the G required to trip the valve are unimportant and can be disregarded.

d. The valve regulates pressure adequately at various G levels when the input gauge pressure varies from 10 to 125 pounds per square inch. Centrifuge performance of the valve with a 246 gram weight and a 63 gram piston is shown in Figure 57. The pressure rate per G can be varied by varying the mass of the top weight.

e. Tests were conducted to determine the free air flow from the suit port of the valve with piston held in the fully down position and with the pressure at the suit port maintained at four pounds per square inch. Thus this is the air flow which will be delivered to the pneumatic suit which is pressurized at four pounds per square inch. Results are plotted in Figure 58. One sees that a flow of 10 cubic feet per minute which can be considered adequate to inflate a G suit in approximately two seconds is maintained when valve input pressure is 6.5 pounds per square inch. Pressure drop across the valve in the fully opened position can be obtained from the input pressure and suit port pressure gauge reading.

f. A pressure relief valve unit made to be applied to the suit port side of the Clark-Cornelius valve body has been designed and submitted by the Adel Precision Products Corporation to specifications furnished by ATSC (Figure 59). The unit consists of a spring controlled poppet head opening into the channel of the suit port of the principal valve. Compact and light, it is attached directly to the valve body. The poppet valve cracks at 10 pounds per square inch and was designed to limit suit pressures to 10 ±.1 pounds per square inch in the face of input pressures ranging from 10 to 80 pounds per square inc. A 50 mesh wire screen will be placed beneath the relief valve unit, screening the suit port of the valve, to protect the valve from such particulate matter as might be sucked into it as a consequence of the negative pressure

Table 2.

Air Loss from Modified Clark-Cornelius Valve at 1 G, C.F.M.

Input Press. p.s.i.	Tank Port Closed Valve Number							Tank Port Open Valve Number						
	1	2	3	4	5	6	Mean	1	2	3	4	5	6	Mean
10	2.0	2.0	2.0	1.0	2.0	1.0		2.0	2.0	2.0	2.0	2.0	2.0	
20	2.0	2.0	2.7	2.0	2.2	2.0		2.8	2.2	3.0	2.0	2.8	2.0	
30	2.8	2.5	3.8	2.3	3.3	2.3	2.8	4.0	3.3	4.5	3.0	4.1	3.0	3.6
40	3.7	3.5	4.8	3.0	4.3	3.0	3.7	5.1	4.2	5.8	3.8	5.3	3.8	4.7
50	4.7	4.3	5.8	3.8	5.3	3.7	4.6	6.3	5.4	7.1	4.6	6.5	5.0	5.8
60	5.6	5.2	7.0	4.6	6.3	4.5	5.5	7.4	6.4	8.6	5.6	7.7	5.8	6.9
70	6.6	6.0	8.2	5.3	7.3	5.3	6.4	8.6	7.4	10.0	6.5	9.0	6.8	8.1
80	7.5	6.8	9.3	6.0	8.3	6.0	7.3	10.0	8.5	11.4	7.5	10.3	7.8	9.2

Table 3.

Effect of Valve Input Pressure on G Required to Trip the Modified Clark Cornelius Valve.

Input Pressure p.s.i.	G Required to Initiate Suit Pressurisation
10	Between 1.5 and 2.0
20	"
30	"
40	"
50	Between 2.0 and 2.5
60	"
70	"
80	"

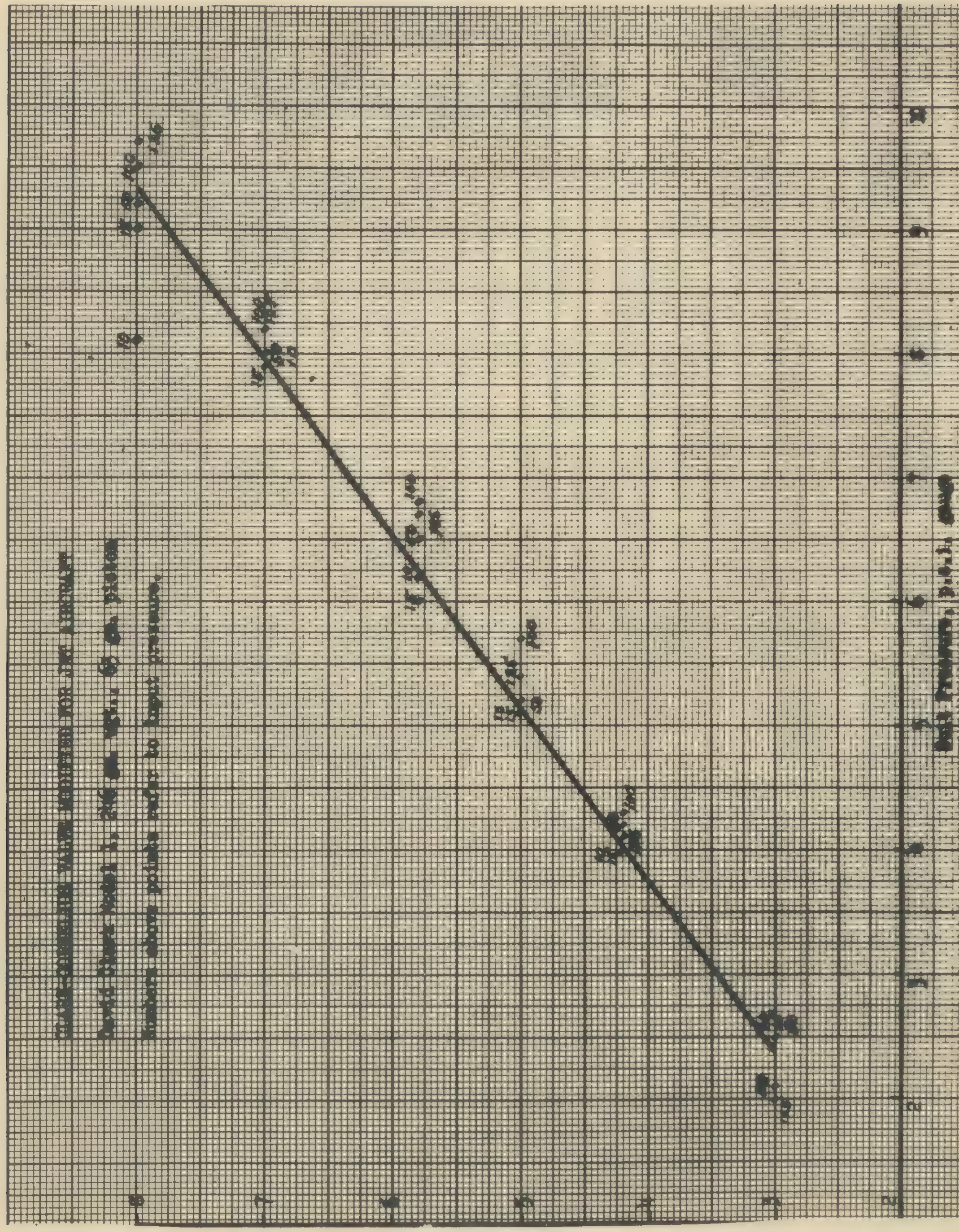


Figure 57 4528B-A M L

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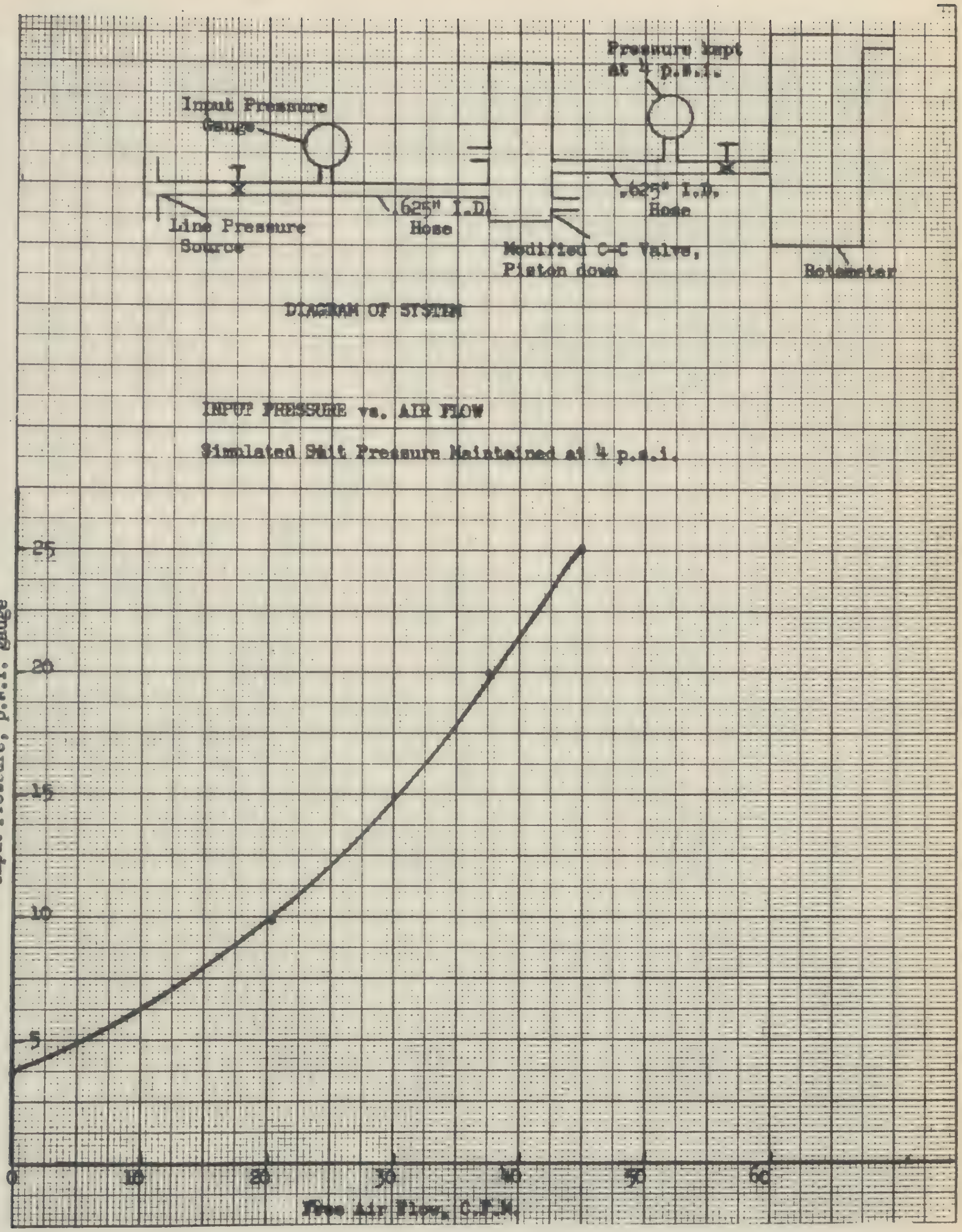


Figure 58

4528C-A M L

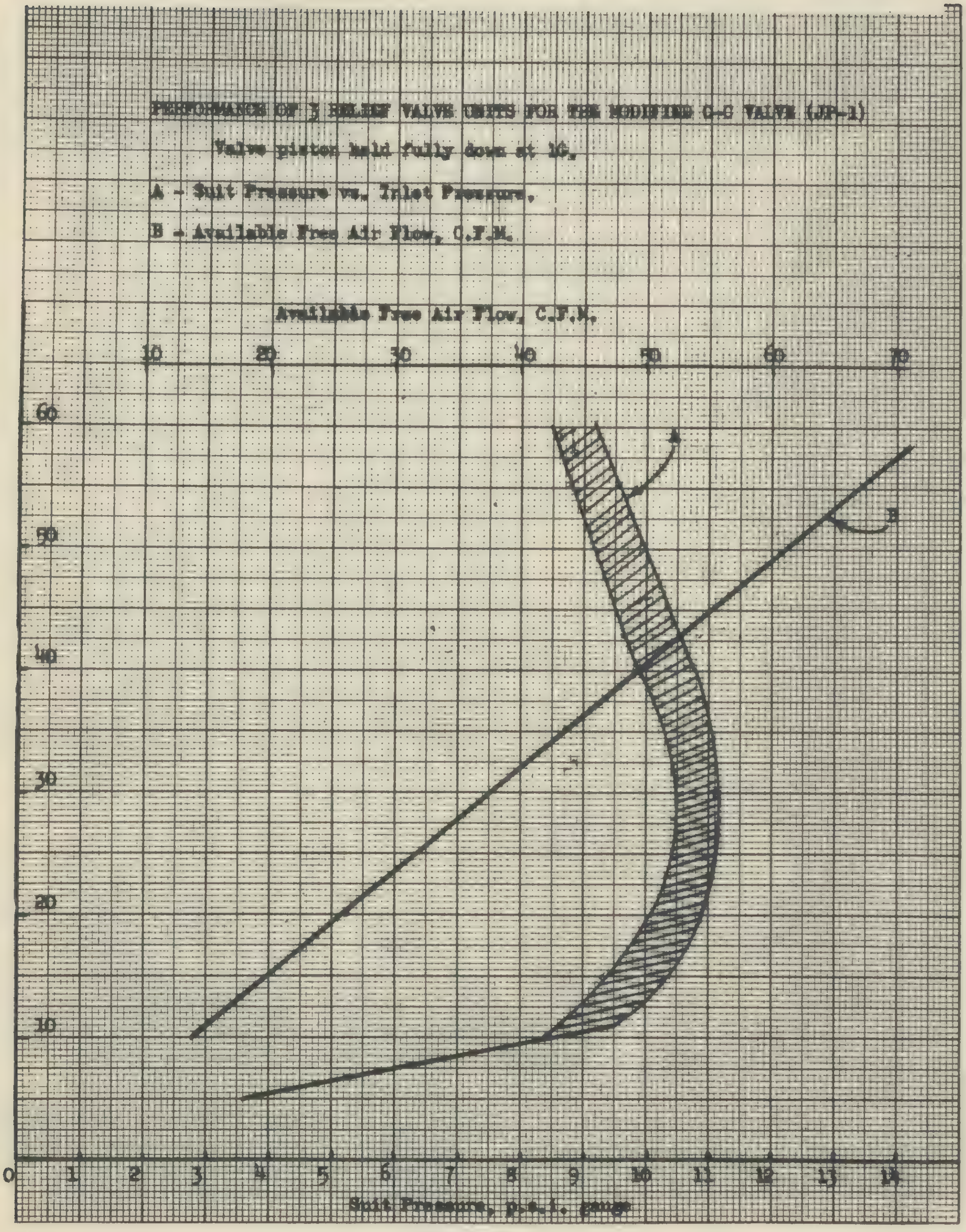


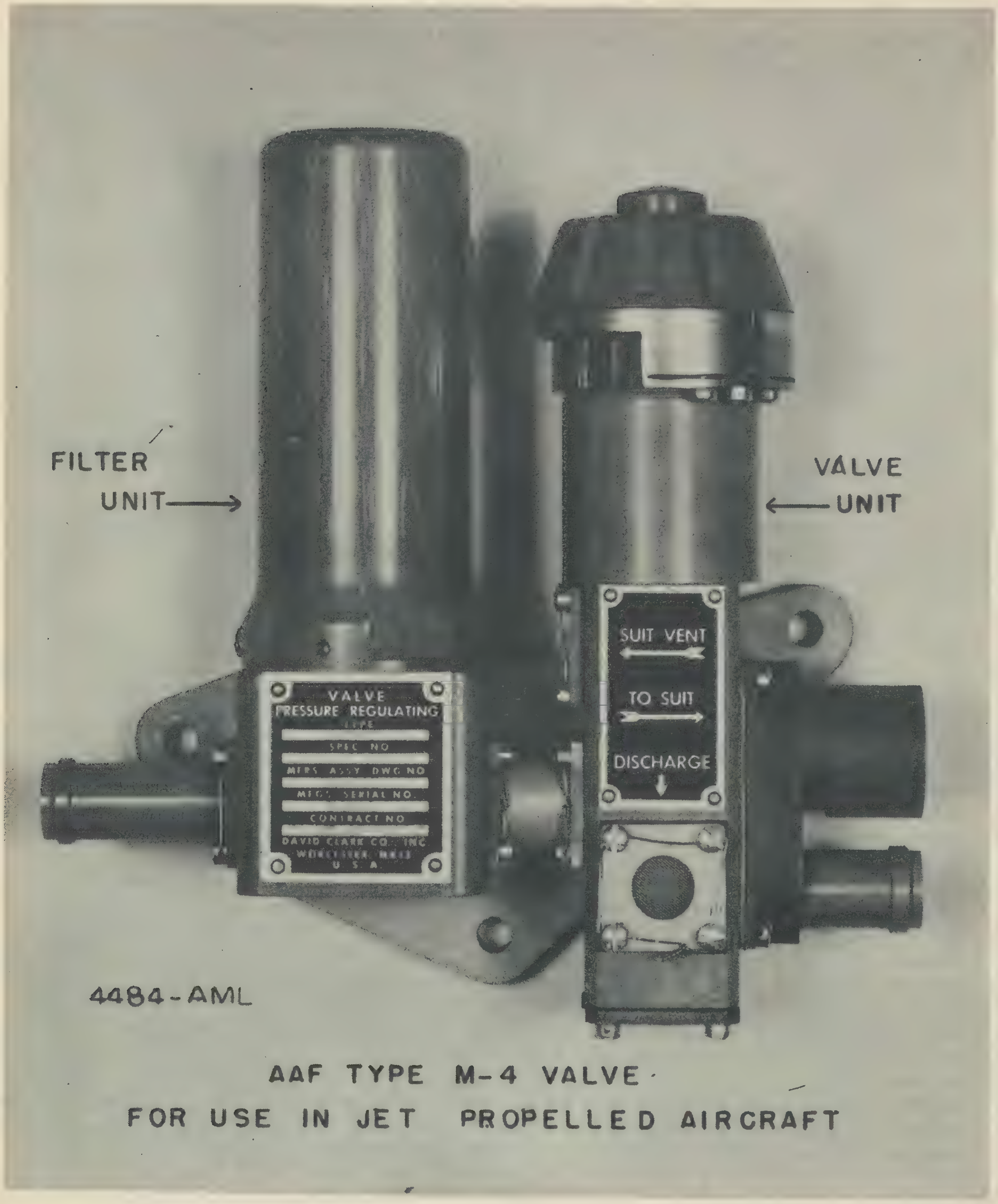
Figure 59

4528E-A M L

described in paragraph 4a above. The relief unit limits suit pressure to 10 ± 1 pounds per square inch, and this pressure would appear in the suit if the piston in the main valve were to stick in the down position. This pressure, though well below that necessary to cause a suit to burst, will be very uncomfortable to the wearer who would disconnect from the air line at once.

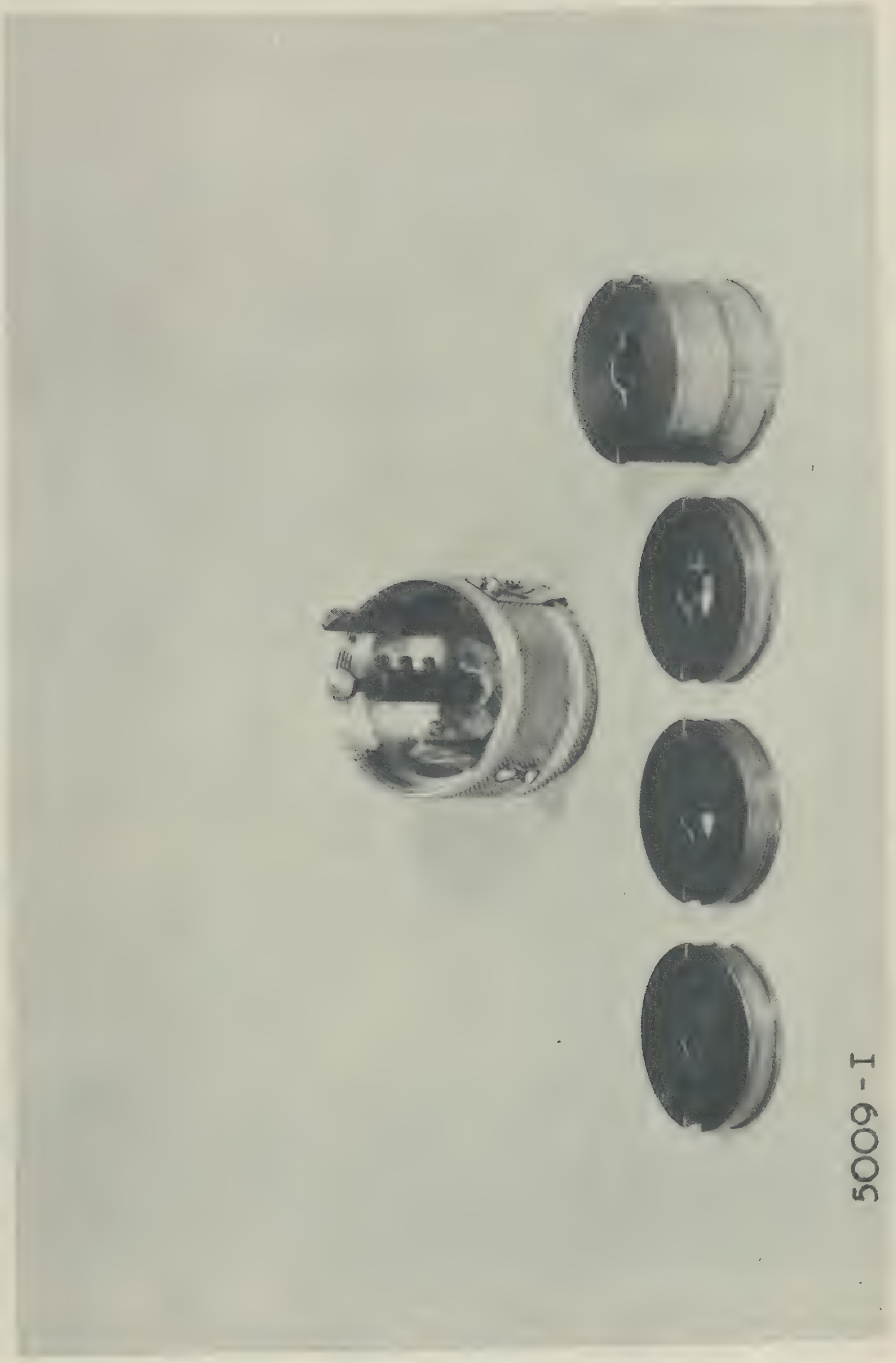
g. To provide filtration of inlet air to this valve, filter element, hydraulic, AN part number 6235 has been incorporated into a housing attached to the inlet port of the G valve. This filter element is made of cellulose formed in vertical convolutions, filters particulate matter to a size of 10 microns, and has a filter area of approximately 85 square inches. Pressure drop through a clean filter element at 75 degrees Fahrenheit and sea level pressure is 9 inches H_2O (0.325 p.s.i.) at a flow of 10 c.f.m. A special housing was designed by the David Clark Company for this usage because the housings available for use with this filter element do not have large enough inlet and outlet orifices. Air channels in the housing made for use with the G valve have areas equivalent to or greater than that of a 1/2 inch I.D. orifice throughout. The valve and filter units, connected by an airway, are mounted to a bracket by which the assembly is attached as a single unit to the airplane (Figure 60).

h. It is a common observation among those who have introduced anti-G suits to pilots that although comparatively low suit pressures are often considered undesirably severe by pilots during their first few trials of the suit, most men come to want higher pressures after they have become accustomed to the feeling of pressurization. Thus in order to gain pilot acceptance for the G suit, pressures used during the indoctrination period must be kept low. Use of an adjustable valve will allow this to be done and provide higher pressures if and when they are desired. An adjustable valve can also be expected to render suit sizing less critical than is the case where only a single pressure rate is available. Pressure regulation can be achieved by varying the total compensating weight of the pressure regulating valve. The procedure in the case of the Clark-Cornelius type of valve has been to segment the weight above the piston and provide means for selecting various combinations of these segments to act on the piston at a given time. One method, developed at the Mayo Aero Medical Laboratory, is pictured in Figure 61. The compensating weight is divided into four parts, each of which is keyed onto a central shaft in the cap of the Clark-Cornelius valve. The position of the shaft, adjusted by turning the top of the cap, determines the number of weights which are free to act on the underlying valve piston and therefore which of four pressure rates per G is in effect. A similar system employing four bucket-shaped concentric weights was developed by the David Clark Company. Finally, Mr. Clark has developed a unit which provides selection of two pressure rates per G, an arrangement which is thought to be sufficiently flexible and simple for practical use. This unit is shown attached to the valve in Figure 60. Pressures are selected by turning the top of the valve. With the valve in any given position a turn of the top in either direction selects the other pressure rate. Pressure rates of 0.9 and 1.4 p.s.i. per G have been specified for the first valves to be used by the AAF.



AAF TYPE M-4 VALVE
FOR USE IN JET PROPELLED AIRCRAFT

FIGURE 60



SEGMENTED WEIGHTS TO MAKE CLARK CORNELIUS VALVE ADJUSTABLE. (MAYO AERO MEDICAL LAB.)

FIGURE 61

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VII. Disconnect Fittings for Pneumatic Anti-G Suits.

A. General requirements.

1. The two components must mate easily and with positive action.

2. The force required to separate the two parts should be no less than five pounds and no greater than 20 pounds. There must be no tendency for the parts to separate as a result of the forces accompanying acceleration or bodily movement on the part of the pilot. It should be possible to disconnect the parts with one hand. The connection should separate from traction alone when the pilot bails out without preliminary disconnection.

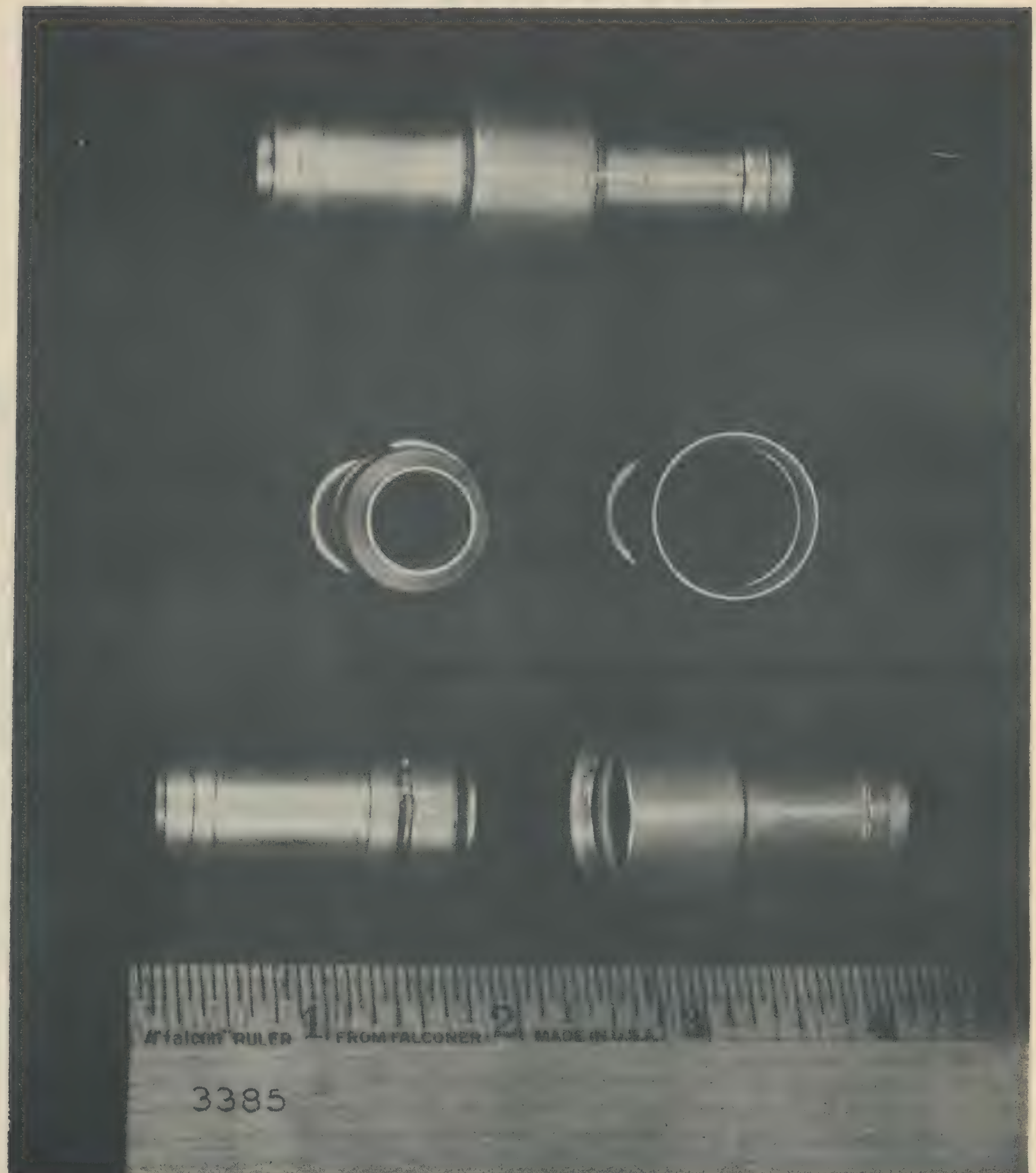
3. The connection must neither leak nor separate when subjected to an internal air pressure in excess of that which occurs during inflation of the G suit. Stability when pressurized to 40 pounds per square inch is not difficult to achieve and offers a sufficient factor of safety.

4. The internal diameter of the air passage must be as large as that of the rest of the line which carries air to the suit so that a flow restricting orifice is not introduced into the system. It has been found that an internal diameter of 1/2 inch is satisfactory.

5. The disconnect must function satisfactorily over a temperature range of minus 60 to plus 120 degrees Fahrenheit (minus 51.1 to 71.1 degrees Centigrade).

B. The C-ring type of disconnect (Berger Brothers Company). The first disconnect fitting used for single pressure suits by the USAAF employed a C-ring on the male component to seat in a circular groove in the female part. The male portion was attached to tubing in the cockpit; the female portion was attached to the G suit (Figure 62). An air-tight seal was accomplished by a rubber washer in the female part which acted as a seat for the end of the male component. Though preliminary models appeared to be satisfactory, production models were unsatisfactory because mating of the male and female sections was often not positive and because the force required to separate the connectors was extremely variable. Furthermore because of its design, this disconnect fitting could not easily be separated with one hand. Because of these defects the C-ring type of disconnect was abandoned by the AAF in favor of the type described in paragraph D below.

C. The Cornelius disconnect fitting (US Navy). The Cornelius disconnect fitting consists of male and female parts, the male attached to the G suit and the female to the tubing in the airplane. The male portion has a flanged end which is secured in the socket of the female part by three ball bearings mounted in the side walls of the socket. C-shaped leaf springs in a groove in the body of the female member apply force to the bearings. Sealing is achieved by a neoprene O-ring in the body of the female section. The female component is mounted securely to the seat by a 90 degree angle bracket (Figure 63). If this connector is separated by a force applied in its long axis, a pull of 50 to 60 pounds is required. The connector separates easily, however, if subjected to a breaking force applied at an angle from the long axis. To avoid need of



BERGER BROS.' DISCONNECT FITTING FOR ANTI-G SUITS

FIGURE 62

U.S. NAVY DISCONNECT FITTING

FIGURE 63

excessive breaking force the female part is mounted to the seat in such a manner that an upward pull, as when a pilot bails out, results in an angular breaking movement on the disconnect. The fact that the female part of the disconnect is firmly mounted to the seat demands that the tube attached to the G suit be long. The tube attached to the suit should never be long enough that a pilot can get out of the cockpit while the connector is still joined, since the force required to separate any connector is greatly increased if it must be transmitted through a tube bent 180 degrees over the edge of a cockpit and one could fail to disconnect under these circumstances. The fact that the Cornelius fitting breaks easily when its parts are subjected to a sidewise force causes it to separate occasionally during acceleration or in response to movements of the pilot when one member is firmly anchored. Because of these observations the Cornelius connector was modified for AAF use.

D. The modified Cornelius disconnect fitting (USAAF). The Cornelius disconnect fitting was changed as follows: The bracket was removed from the female member and the nipple of that fitting was placed at an angle 35 degrees from the straight (Figure 64). Thus no matter how the disconnect is pulled it will always be separated by a sidewise force. Furthermore, because both parts of the disconnect fitting are free and can move to adapt themselves to forces which might otherwise tend to separate them, the tendency to separate during acceleration or as a result of movements of the pilot is eliminated. Since the disconnect hangs freely it can be used with the suits which have short inlet tubes.[8] For AAF use, the tube bearing the female part of the disconnect in the cockpit is provided with a hard rubber collar ten inches from the disconnect fitting. This tube passes freely through a hole in an angle bracket attached to the seat, so that when the connector is not in use it rests on this bracket. The disconnect can be pulled beyond the bracket a distance of ten inches at which point the rubber collar on the tube engages the bracket. If the tube is pulled further, as in bailing out, separation of the disconnect occurs automatically. A report on tests of this disconnect fitting at the US Naval Air Test Center, Patuxent River, Maryland, contains the recommendation that it be considered as a substitute for the original Cornelius model for use by the US Navy.[66]

MALE FITTING ON G SUIT

FEMALE FITTING IN PLANE

DUST PLUG

ORAL INFLATION VALVE FOR MALE FITTING

AAF MODIFICATION OF CORNELIUS DISCONNECT FITTING

FIGURE 64

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VIII. Factors Involved in the Protection Afforded by Anti-G Suits.

A. Introduction. The different types of anti-G suits described earlier in this report afford the wearer varying degrees of protection against the effects of increased positive G. The question may be asked, what factors determine the degree of G protection provided by an anti-G suit? Four principal variables can be considered: (1) the pressure or pressures to which the suit is inflated, (2) the parts of the body which are pressurized, (3) the time of pressurization of the suit in relation to the onset of acceleration, and (4) the order in which various parts are pressurized.

B. The effect of variation of suit pressure on G protection afforded by the suit.

1. The pressure applied by a G suit to the underlying parts of the body may differ from the pressure to which the bladders of the suit are inflated. For example, in one instance Lamport and Herrington found that pressures exerted on the legs 12 inches above the ankle by a G-2 suit varied at different points around the extremity from 6 to 0.3 p.s.i. when bladder pressure was 6 p.s.i.[53] Further variation in actual applied pressure can be expected to result from variations in the fitting of such suits on different subjects. None the less, significant data have been obtained in experiments in which the G protection afforded by various suits is related to the air pressure within the bladders, with actual applied pressure neglected.

2. Gradient pressure versus single pressure. In early developmental work on G suits emphasis was placed on providing a gradient of pressure, higher over the lower parts of the body, to compensate for the theoretically higher hydrostatic pressures in the veins in these regions. The water suit is ideal, according to this concept, since it automatically provides a perfect pressure gradient with higher pressures in the lower parts of the suit. Application of this concept led to the use of multiple pressures in pneumatic suits. This type of pressurization is exemplified by the gradient pressure suit (AAF type G-1) and the Cotton suit. The penalty for this type of pressurization is increase in weight and complexity of both suit and valve. Critical studies failed to substantiate the necessity for gradient pressure as it is used in the GPS. Protection afforded by the type G-2 single pressure suit and by the GPS inflated to a single pressure is as good as that provided by the GPS inflated to gradient pressures (Table 1). Furthermore, were there any decisive advantage to a gradient pressure system, a gradient of applied pressure could be achieved with a single pressure system, since the size of a bladder as well as the pressure to which it is inflated determines the pressure applied to the underlying tissues. Thus one should be able to apply a gradient pressure to the extremities with a single pressure suit, similar to type G-2, by using bladders of trapezoidal shape with the broadest parts distal. Lamport and Herrington succeeded in accomplishing this in another way with the PIS, a single pressure suit.[53]

3. The protection afforded by a given G suit varies directly with the pressure to which it is inflated. Data from the Mayo Aero Medical Unit indicate that the FFS with 4.7 liters of water gives an average visual protection of

1.0 G; full of water, 1.4 G.[59] Taking the midpoint of the hydrostatic column as a point which gives an average pressure, and assuming columns of 18 and 25 inches respectively, pressures become 0.325 and 0.47 p.s.i. per G.[49] Inflated with air at a pressure of 1 p.s.i. per G, the FFS gives a protection of 2.2 G (Figure 65A).[49] The same type of result was obtained with the AOS (Figure 65C) and the GPS (Figure 65B).[61] This information from two subjects wearing the GPS, AOS and FFS is summarized according to protection afforded ear pulse and ear opacity in Figure 66. As another example, the University of Southern California reports average visual protection to be 1.2 G for the Z-2 suit inflated to a pressure of 1 p.s.i. per G beginning at 1.75 G, and 1.6 G for the same suit inflated to a pressure of 1.5 p.s.i. per G beginning at 1.75 G (Table 1).[42]

C. <u>Relative effectiveness of pressurization of different parts of the body</u>.

1. Wood et al[61] obtained the following data in a centrifuge study of the relative importance of the components of the arterial occlusion suit in providing G protection for 12 subjects (Figure 67):

a. Inflation of the leg bladders alone afforded 0.2 G protection against visual symptoms resulting from exposure to positive G.

b. Inflation of the abdominal bladder alone provided 0.7 G protection against such visual symptoms.

c. Inflation of both leg and abdominal bladders provided protection of vision of 1.4 G, double that obtained with abdominal bladder alone.

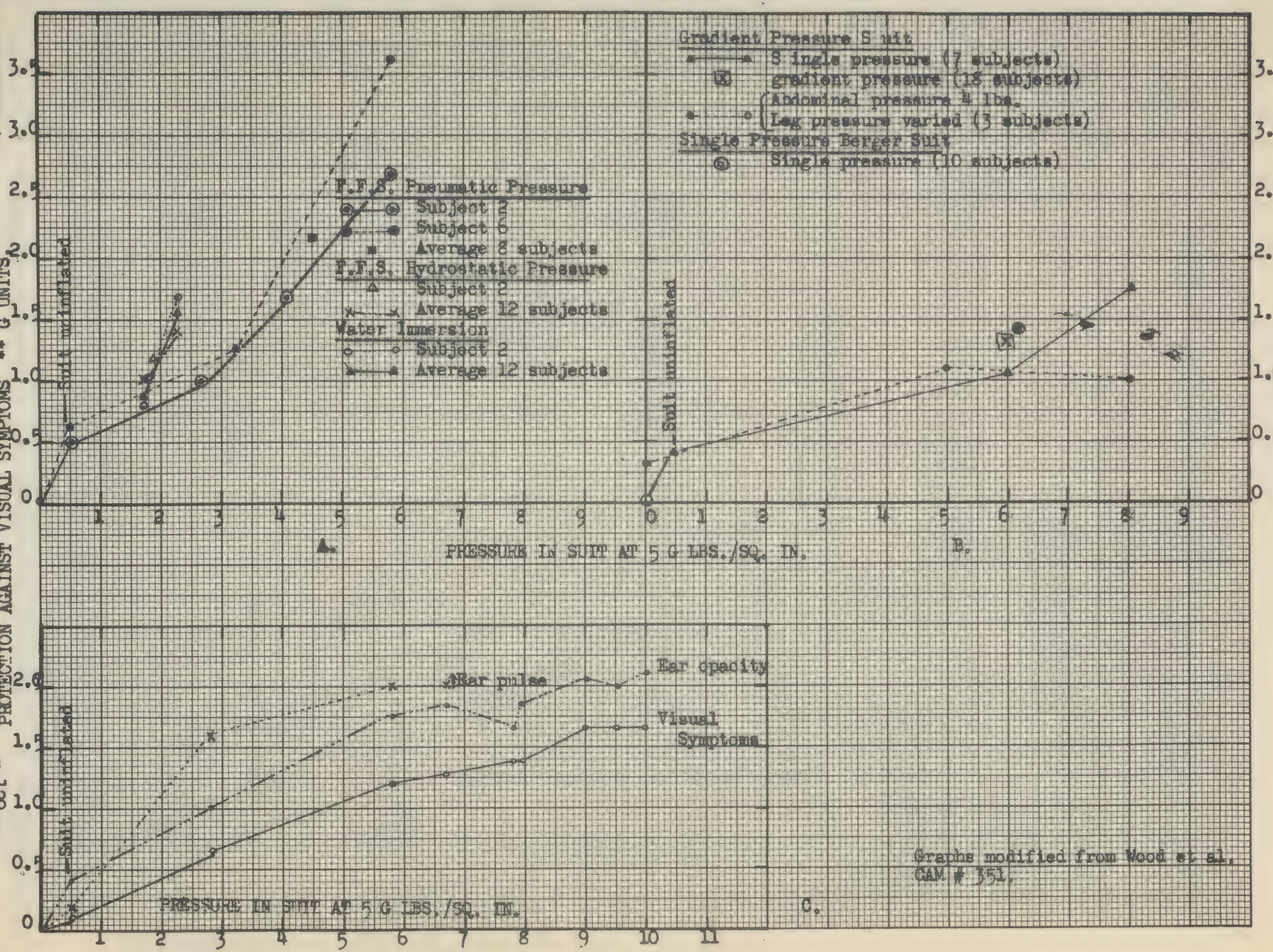
d. Inflation of arm bladders alone did not give measurable G protection.

e. Inflation of leg, abdominal, and arm bladders provided protection of vision of 2.0 G, an increase of 0.6 G over that afforded by leg cuffs and abdominal bladder.

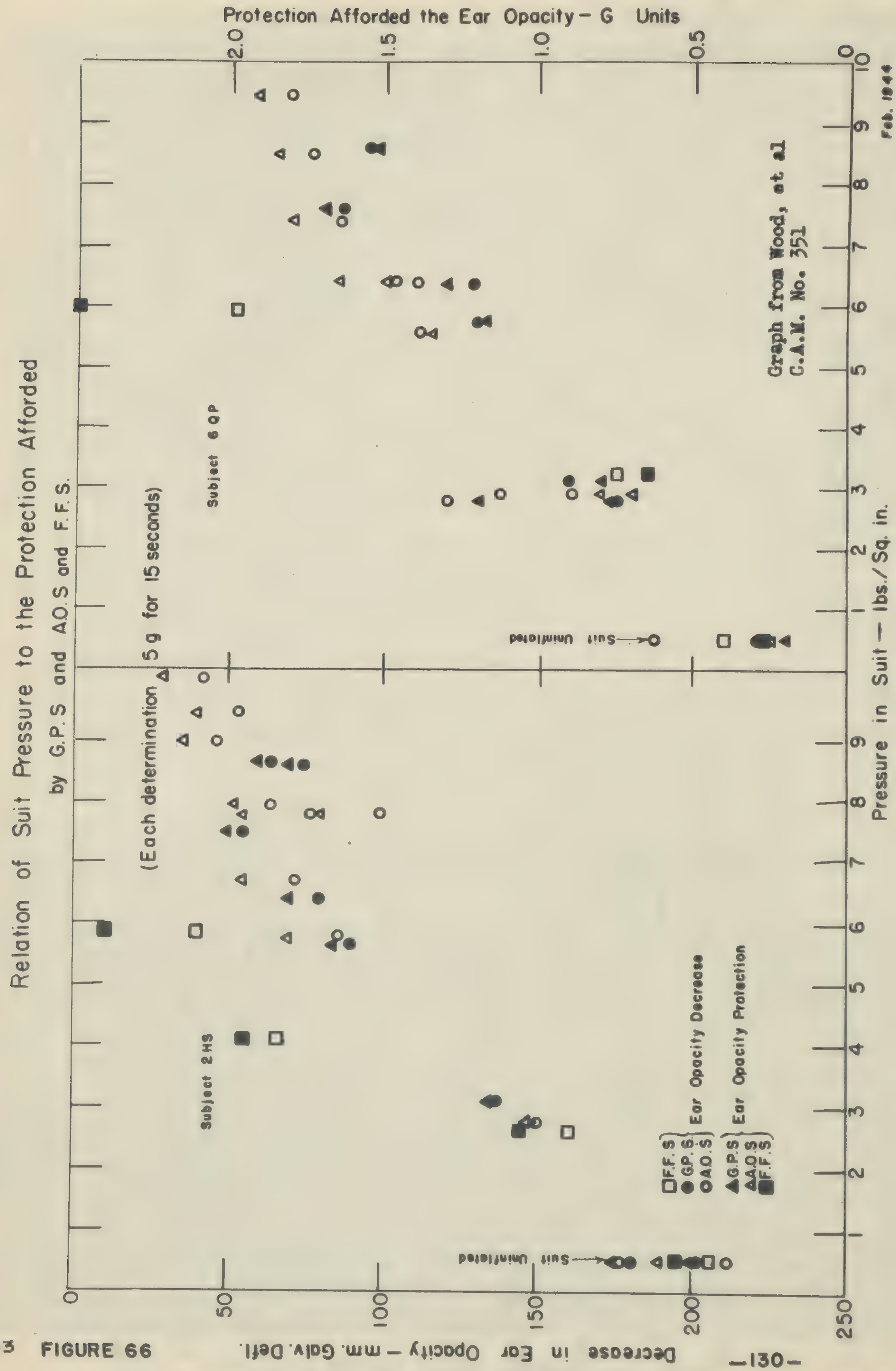
2. These data indicate that the most important component determining the protection afforded by the AOS is the abdominal bladder. This fact is emphasized by a comparison of protection figures obtained with arterial occlusion suits with abdominal bladders of different sizes. G protection was uniformly increased as abdominal bladder volume increased. The importance of the abdominal pressure was noted in another way with the GPS. G protection increased uniformly when leg bladder pressure was maintained at 1 p.s.i. per G and abdominal bladder pressure was increased. When abdominal bladder pressure was held constant at 4 p.s.i. and leg pressure was progressively increased, G protection increased until 1.2 G was reached, then remained nearly constant. Thus G protection was relatively independent of leg bladder pressure but varried directly with abdominal bladder pressure.[61]

3. It can be concluded (1) that the degree of protection afforded by the suits tested is determined principally by the efficiency of the abdominal bladder,

... PROTECTION, FFS,AOS,GPS.
(Each determination at 5 G. for 15 seconds.)

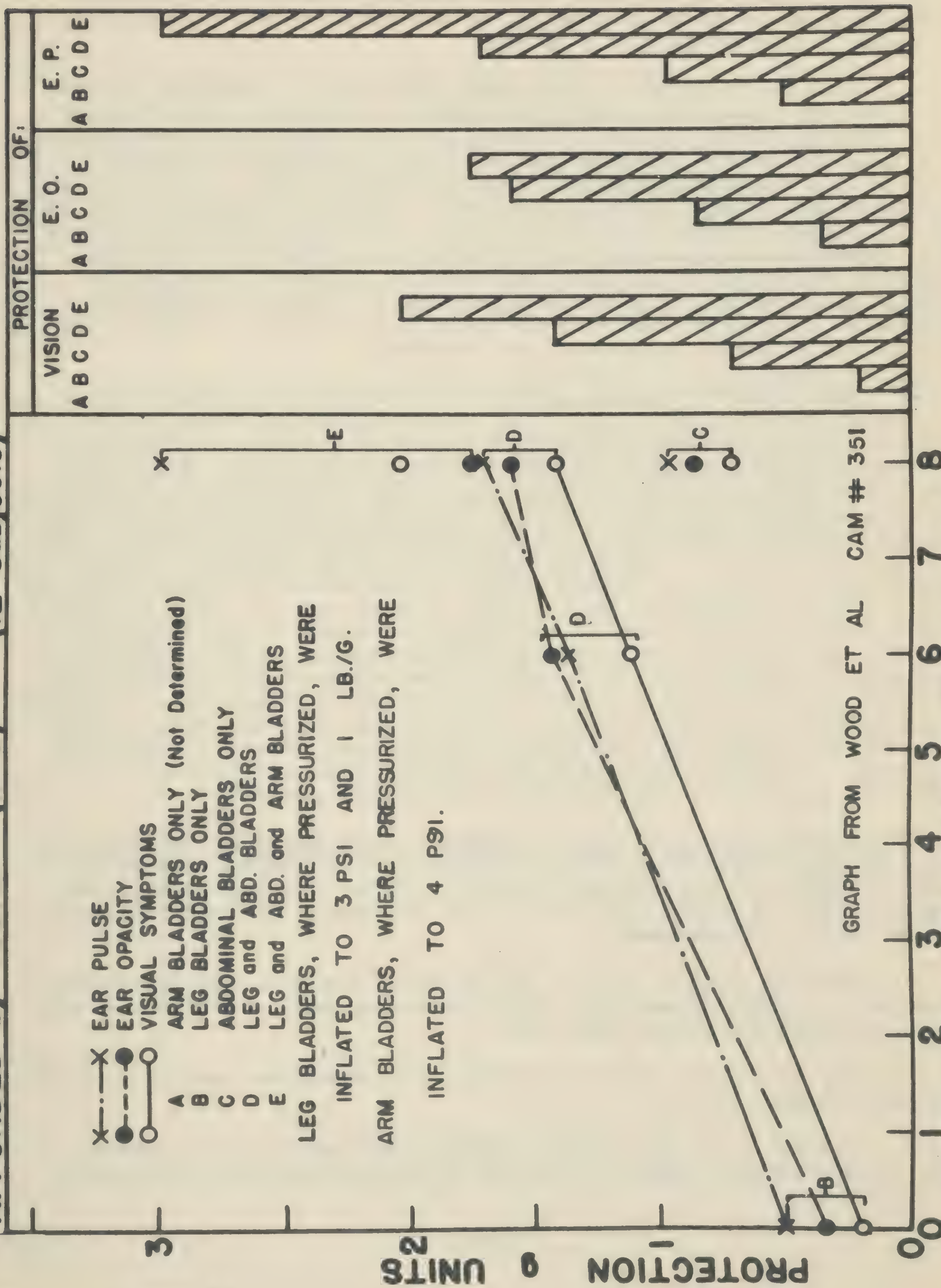


5433" FIGURE 65.



5433 FIGURE 66

RELATION of the ELEMENTS PRESSURIZED to the PROTECTION AFFORDED by A.O.S. (M-5) (12 Subjects)



5433 FIGURE 67

and (2) that pressure on the legs, though relatively ineffectual by itself, greatly augments protection afforded by the abdominal pressure. Furthermore, the degree of leg pressure is not critical.

4. From the foregoing it follows that the degree of protection afforded by a given suit can best be varied by increasing or decreasing the efficiency of the abdominal bladder, either by varying its size and/or the thickness it can assume when inflated or by varying the pressure to which it is inflated. If the goal is the maximum protection possible, the limiting factor will be the discomfort caused by application of pressure to the abdomen. Discomfort in the legs due to high pressures need not be a limiting factor since leg bladder size can be reduced to compensate for higher pressures delivered to the abdominal bladder in single pressure systems. The degree of discomfort caused by the abdominal pressure varies not only with the pressure to which the abdominal bladders are inflated but also with the design of the bladder, the fit of the suit, and the subject's reactions to such pressure.

5. This information can be applied in a practical way to various types of G suits. Models of the AOS with large abdominal bladders offered a high degree of G protection when inflated to the rather high pressure of 2 p.s.i. plus 1 p.s.i. per G. Abdominal discomfort, however, was marked, and played a role in denying the suit pilot acceptability. Some of the nylon bladder suits which led to the Z-1 (G-4) suit had large abdominal bladders and offered as much as 1.7 G protection (Table 1). Again abdominal discomfort was noticeable, and since a protection of 1 to 1.5 G was effective in current aircraft, abdominal bladder size was reduced to increase comfort at the expense of G protection. The size of abdominal bladders in the G-3 series of suits was kept small to increase comfort, comfort being achieved by accepting a protection of only approximately 1 G. With the information at present available, increase in G protection by G suits can be achieved only at the cost of some degree of comfort during suit inflation. Design studies directed at achieving more even application of pressure to the abdominal region might be able to improve this situation should greater protection become necessary, and should be carried out. Reports indicate that the capstan principle as employed in the pneumatic lever suit provides more comfort during pressurization than the direct pressure method.[54]

D. <u>Relationship between the time of inflation of the G suit and the G protection it affords.</u> Henry, Clark, Tracy, and Drury have studied the changes in protection against visual symptoms provided by the G-4 (Z-1) suit when it was rapidly inflated to 5 p.s.i. at various times relative to the onset of acceleration.[48] Their data indicated:

1. That the pressure could be applied at any time less than two minutes before the attainment of maximal G without decreasing suit protection more than 20 per cent below the maximal attainable.

2. The optimal time for suit inflation lay between the start of acceleration and attainment of 3 G.

3. A delay of the time of full inflation until more than five seconds after the attainment of maximal G resulted in a 20 per cent loss of potential

suit protection and further delay increased this loss greatly (Figure 68).

4. Prolongation of inflation time, if great enough, can result in loss of potential suit protection. With the G-4 suit, 2 p.s.i. suit pressure was found to give 40 to 50 per cent of the protection afforded by 5 p.s.i. pressure. The time after onset of acceleration at which 2 p.s.i. pressure was reached determined the protection achieved. If the critical two pounds pressure was achieved in four seconds after onset of acceleration observed protection was over 80 per cent of potential protection. When inflation rate was such that 2 p.s.i. pressure was not developed until more than six seconds after attainment of maximal acceleration, over 50 per cent of potential suit protection was lost (Figure 69).[48]

E. The effect on G protection of varying the order in which various parts are pressurized during inflation of the G suit. The idea of progressive pressurization of the G suit, accomplished by having air enter the suit at the ankles and successively pressurizing the legs, thigh, and abdomen has been often discussed by workers in the field. Aside from preliminary data collected at the Mayo Aero Medical Laboratory on an early suit of this type made by the David Clark Company, little work has been done with this concept. It is possible that use of this method of inflation would enhance protection by milking blood from the extremities toward the heart during inflation of the suit.

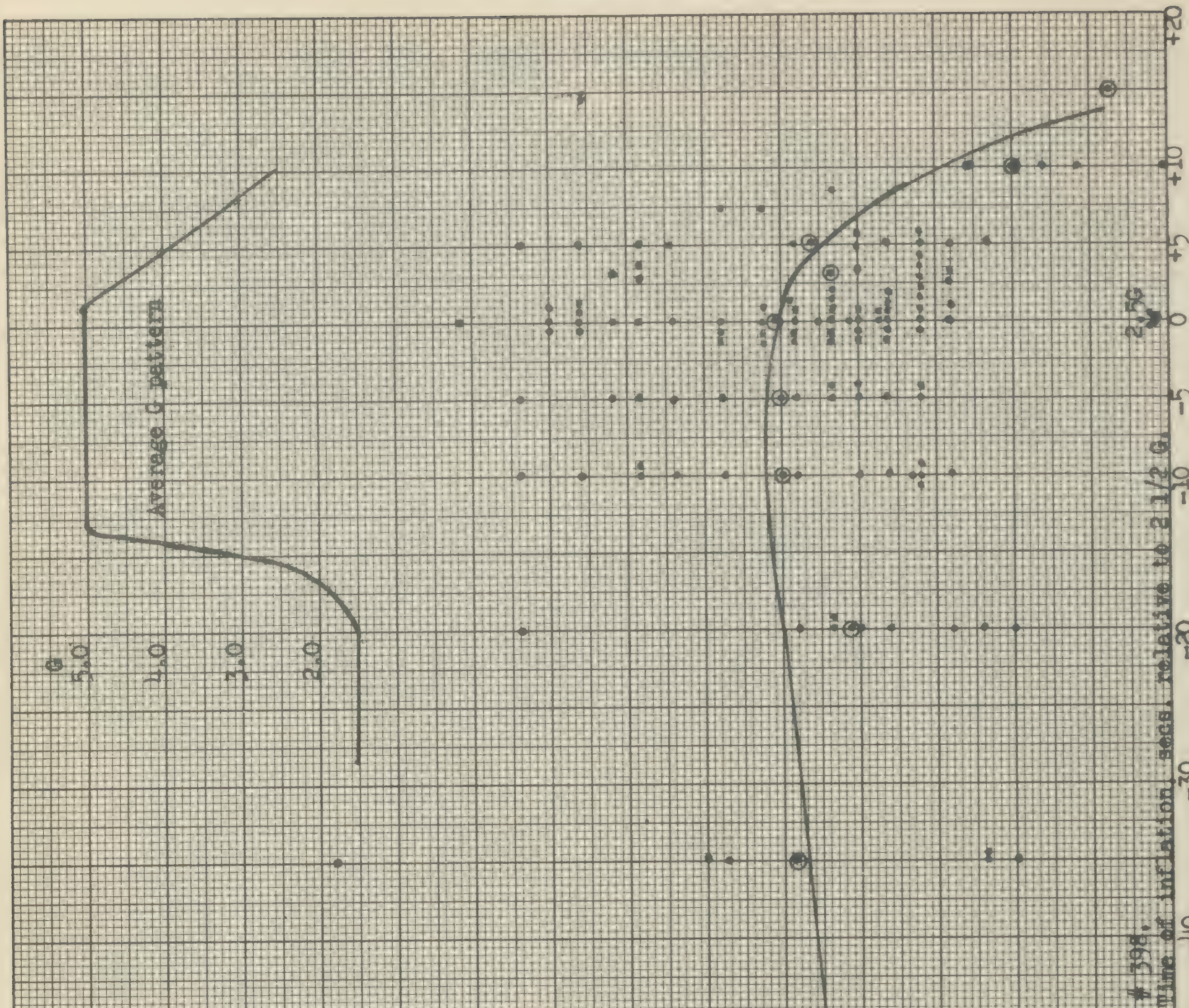
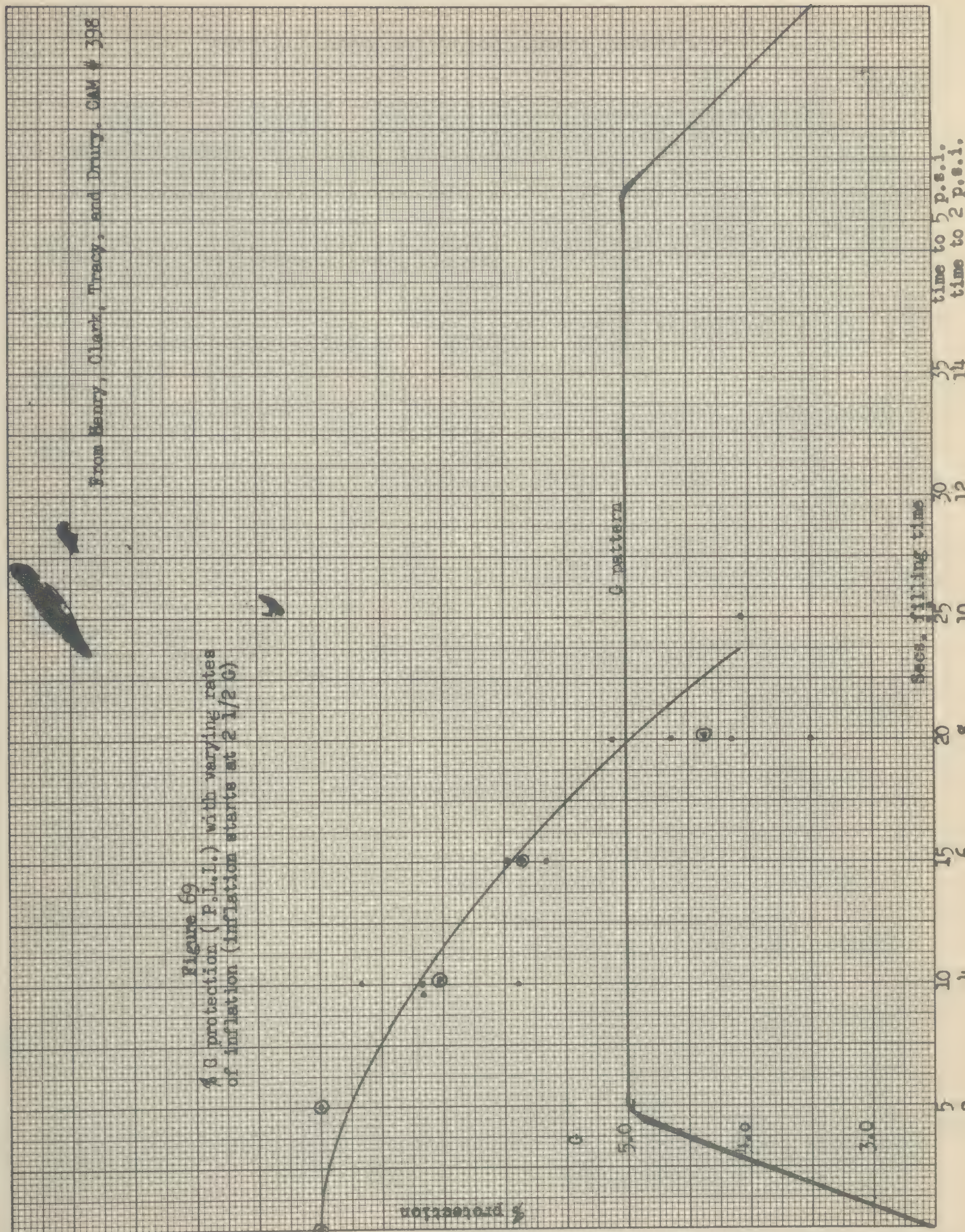


Figure 68.
G protection (P.I.L.) when suit
is rapidly inflated (0.8 secs.)
at various times relative to 2 1/2 G.
Average G pattern
G
5.0
4.0
3.0
2.0
Protection - G units
From Henry, Clark, Tracy, and Drury. CAM # 398.
Time of inflation, secs. relative to 2 1/2 G.
2.5G
+20
+10
+5
0
-5
-10
-20
-30
-40
-50
-60
-120
3
2
1
5433

FIGURE 68



5433 FIGURE 69.

IX. The Relationship Between Use of the Anti-G Suit and the Stress to Which the Airplane is Subjected.

1. In discussions of anti-G suits the question is inevitably raised whether use of the suit encourages pilots to overstress the airplane. It is commonly stated that onset of visual symptoms as a result of positive G serves as a warning that dangerously high levels are being reached and is used as such by the pilot. It is further stated that prevention of these symptoms will remove the warning signal and increase the possibility of overloading with structural failure. Examination of this argument in the light of some of the facts concerning man's response to positive G (see section III) will demonstrate that it will not stand without considerable qualification. Judging from acceleration-time curves obtained in conventional fighter airplanes in flight, accelerations of 7 to 9 or more G are almost always reached quickly, usually in four seconds or less. It is thus common for the higher G values to be reached in snap pullouts in a time shorter than the latent period of four to six seconds which precedes development of visual symptoms. Therefore, in snap pullouts of this type, visual symptoms cannot be considered a warning signal whether the G suit is worn or not. A gradual approach to G levels of 7 to 9, with sufficient time elapsing for development of visual symptoms, seems almost never to occur in the P-51, P-47, P-38 and P-40 airplanes. In fact most pilots in our experience who have been asked to maintain even 7 G for ten seconds have found it difficult because the aircraft loses speed and tends to enter a high speed stall. The feat is usually accomplished only with considerable practice. Whether the situation is any different with jet propelled aircraft is not known with certainty to the writer. It should change as available power increases.

2. Moreover, properly performed muscular straining, which seems to be used to some degree by all fighter pilots, can raise G tolerance more than the 1 to 1.5 G afforded a relaxed man by present day G suits. If use of the G suit is to be considered dangerous because it encourages overstressing of the aircraft, the same must be said of muscular straining.

3. Should the anti-G suit create such confidence on the part of the pilot that he becomes careless and rough in acrobatic flying, it is conceivable that its use might promote overstressing of the airplane by promoting snap pullouts which would otherwise have been avoided. This fact was realized, and both Army and Navy endorsed the policy of installing visual accelerometers in fighter aircraft and warning new users of anti-G equipment not to exceed set limits.

4. Available studies on the effect of use of anti-G suits on accelerations encountered in flight may be mentioned.

a. In a study carried out by the US Navy at the US Naval Air Test Center, Patuxent River, Maryland, 131 flights were made by 21 pilots in training syllabus flights. Each pilot made at least three flights with the G suit and three without it. Acceleration was measured with a VG recorder, checked in some instances by a recording accelerometer which provided a time record. When 66 flights in which the anti-G suit was worn were compared with 65 flights in which it was not used it was found that use of the suit produced no significant increase in the tendency to exceed technical order restrictions regarding stresses imposed on the F6F-3 and F6F-5 airplanes. In fact some pilots considered increasing suit pressure itself a useful warning signal.[65]

b. In a study carried out by the AAF, accelerations encountered in Eighth Air Force P-51D airplanes in combat over Europe were measured by VG recorders. One hundred and nineteen such records representing 460 hours of flight were used, some from flights with and some from flights without the G suit. Without the anti-G suit the highest positive acceleration noted was 4.3 G, calculated to occur at a frequency of 14 per 1000 hours of flight. With the G suit values of 5.0 G occurred at a frequency of 9 per 1000 flying hours and 6.5 G at a frequency of 3 per 1000 hours of flight. Thus higher positive accelerations were encountered when the G suit was worn though in this series the stress limit of the airplane was not exceeded in either case.[5] These data seem remarkable for the absence of at least occasional values in the range of 7 to 9 G, accelerations which were common in a similar series of combat VG recordings in the Spitfire[6] when no anti-G suit was worn and which occurred in the US Navy series discussed above.[65]

c. Another group of data was collected from combat operations of P-51 airplanes in the Eighth Air Force.[3] In this series maximal G values were read by pilots from the Kollsman accelerometers. Of 118 pilots wearing G suits, maximal G values occurred as follows: 5 pilots, 3.0 to 3.9 G; 16 pilots, 4.0 to 4.9 G; 30 pilots, 5.0 to 5.9 G; 30 pilots, 6.0 to 6.9 G; 17 pilots, 7.0 to 7.9 G; 13 pilots 8.0 to 8.9 G; 5 pilots 9.0 to 9.9 G and 2 pilots 10.0 G. No control series of data similarly collected on pilots flying without the G suit is available. These data do indicate that the stress limits of the airplane, which varied from 6.3 to 7.1 G depending on fuel load, were exceeded in many instances, as was the case with Spitfire pilots flying without G suits.

d. As further evidence that pilots not using G suits do achieve 7 to 9 G in combat, reference is made to data from P-47 aircraft of the Twelfth Air Force performing dive bombing maneuvers against enemy installations in Italy. The maximal G which occurred during the maneuver was read by the pilot from the Kollsman accelerometer after the dive bombing attack was finished. In a group of 28 such readings, 7.0 G occurred 5 times, and 7.5 and 8.0 G each occurred 3 times. In a series of 10 records obtained from the same fighter group in simulated combat dive bombing maneuvers in P-47 aircraft the highest acceleration reported was 6.0 G.[12]

5. Thus there are data to indicate that fighter pilots in combat will occasionally expose themselves and their airplanes to 8 or 9 G, values above permissible limits for some aircraft, both with and without G suits. Though it cannot be said with certainty it is quite possible that use of the G suit may increase the incidence of these high accelerations by removing fear of their physiological consequences. It is improbable that postponement of the warning signal of visual symptoms is in itself the direct cause of any tendency to reach higher accelerations in present day fighter aircraft, as was discussed above. To appraise a problem of this sort one must weigh the advantages offered by a given device against any incidental disadvantages it may have. As an analogy, training in close formation flying is probably the cause of many accidents in flying training. Yet, because of its immense value in combat, no one questions its usefulness. The utility of the anti-G suit in rendering pilots more effective by increasing the magnitude of relatively prolonged positive G they can tolerate with clear vision and clear mental processes and by reducing that type of fatigue

which is the result of frequent repeated exposures to positive G has been amply demonstrated. The evidence indicates that its greatest usefulness is in missions in which encounters with enemy aircraft occur with consequent acrobatics. If exposure to positive G consists of isolated dive bombing attacks or strafing, the G suit appears to be less necessary, though a worthwhile safeguard. Numerous statements of pilots could be quoted describing incidents in which the G suit was considered life-saving. Unless these are to be disregarded one must conclude that the G suit is a worthwhile device which should, like so many other elements of military flying, be used where needed with the care befitting an understanding of its potentialities.

X. Conclusion.

Through the combined efforts of many workers in the US Army Air Forces, US Navy, Royal Canadian Air Forces, Royal Air Forces, Royal Australian Air Forces, Mayo Foundation for Medical Research, the National Research Council with its centrifuge at the University of Southern California, and commercial manufacturers there has been developed anti-G equipment which enhances the efficiency of pilots flying fighter aircraft. The evolution of anti-G suits from heavy restricting equipment to lighter practical garments, together with development of associated pressure regulating valves and disconnect fittings, has been described in this report. In centrifuge tests followed by flight tests and finally use in combat the G suit has been proven to perform the functions for which it was designed. In the situations in which combat conditions made the benefits conferred by the anti-G suit desirable, as in the Eighth Air Force and in many Naval carrier based aircraft, the suit was eagerly accepted and played a role in the enviable record achieved by the American Air Forces in World War II.

XI. Recommendations.

1. It is recommended that the Aero Medical Laboratory, Engineering Division, ATSC maintain research in methods of increasing tolerance of man to forces resulting from acceleration to keep pace with design of new airplanes. As aircraft speeds and available power increase there will be an increase in the problem of effects of acceleration on the pilot, both because the acceleration produced by a given radius of turn is much greater at high than at lower speeds (Figures 70 and 71) and because it is probable that newer aircraft will be able to maintain higher accelerative forces for periods of seven to ten or more seconds without loss of speed and development of high speed stalls than is now the case. It is possible that the problem may be met in some airplanes by use of the prone or supine position. At present, high speed airplanes are being designed in which the pilot is placed in the sitting position and in which G protection by G suits will be needed. Problems such as that of the pressure source for G suits in rocket propelled airplanes will arise.

2. It is recommended that the Aero Medical Laboratory, Engineering Division, ATSC, investigate the problems associated with provision of greater G protection than that afforded by present day suits.

a. If pilots in newer aircraft remain in the sitting position and if it becomes commonplace to maintain let us say seven G for periods exceeding seven to ten seconds many pilots will find present G suits inadequate without auxiliary muscular straining. Suits which offer more protection than those at present in use may be developed. Anti-G suits affording 2 to 2-1/2 G protection in contrast to the 1 to 1-1/2 G offered by current models could be made today, though with some sacrifice of comfort during inflation. Before this is done, basic centrifuge studies should be carried out to learn whether the higher blood pressures occasioned by use of suits of this efficiency are accompanied by any hazard to the wearer. X-ray or X-ray motion picture studies of the heart combined with measurements of arterial blood pressure, venous pressure and heart rate in animals and man during such G protection are needed, both with and without pressurization of the chest by pressure breathing. Should G suits which afford protection in the range of 2.0 to 2-1/2 G be desirable and physiologically safe it is possible that alterations in the design of the abdominal bladder and an increase in the area of the body pressurized could be incorporated in a suit which would provide this protection with less discomfort than has been the case in the most efficient models thus far studied.

b. There is undoubtedly an upper limit of positive G above which it is unsafe to protect individuals with anti-G suits. One of the most important physiological limiting factors, as discussed in the previous paragraph, would be the high arterial blood pressure which must be achieved to preserve vision at high accelerations of more than five to seven seconds duration. In the present opinion of the writer this upper limit for protection of seated pilots is approximately eight G. Experiments of the type suggested in paragraph 9a above would test this assumption. If aircraft were to be designed in which pilots would be expected to withstand greater positive accelerations a change in

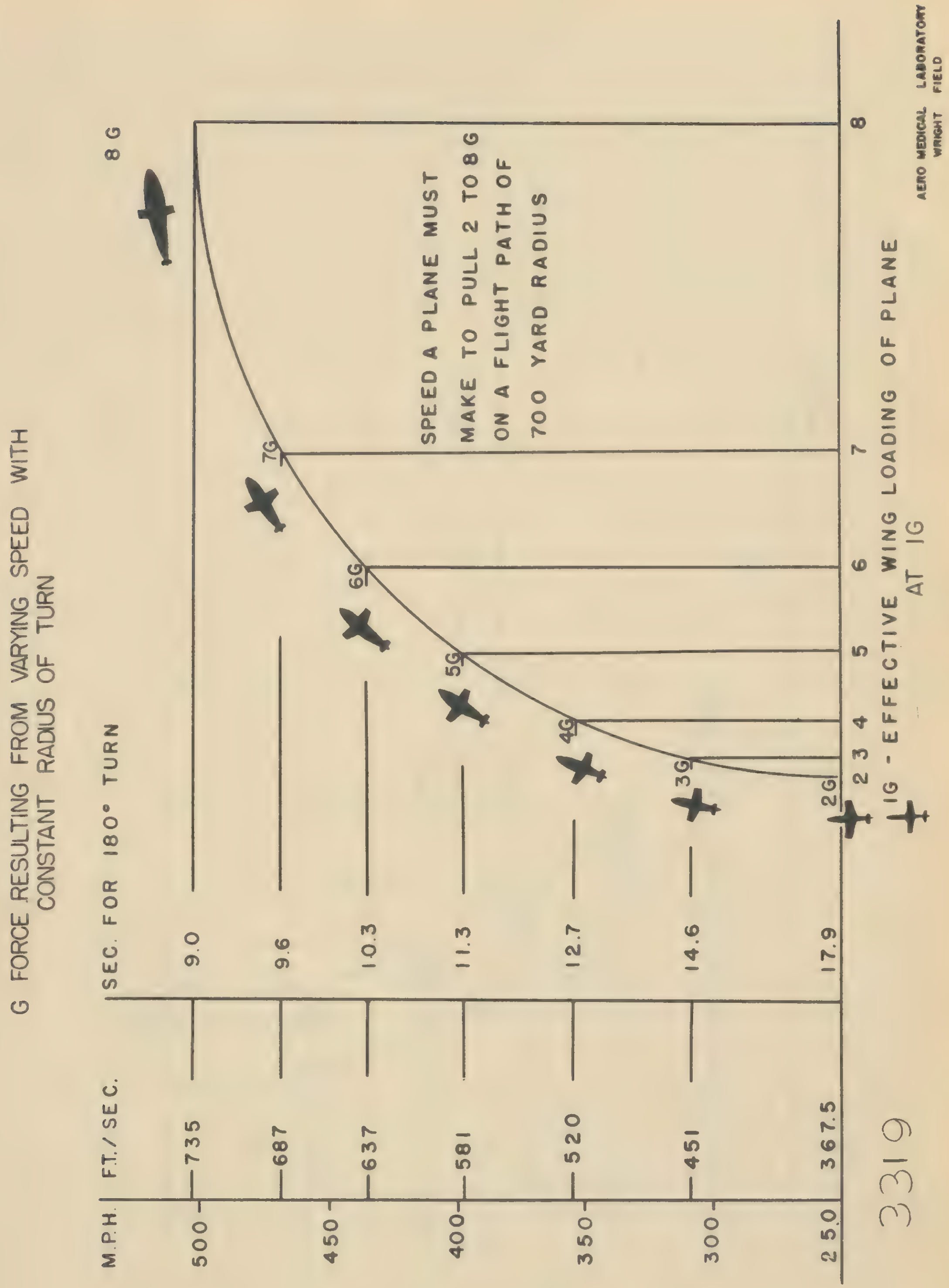


FIGURE 70

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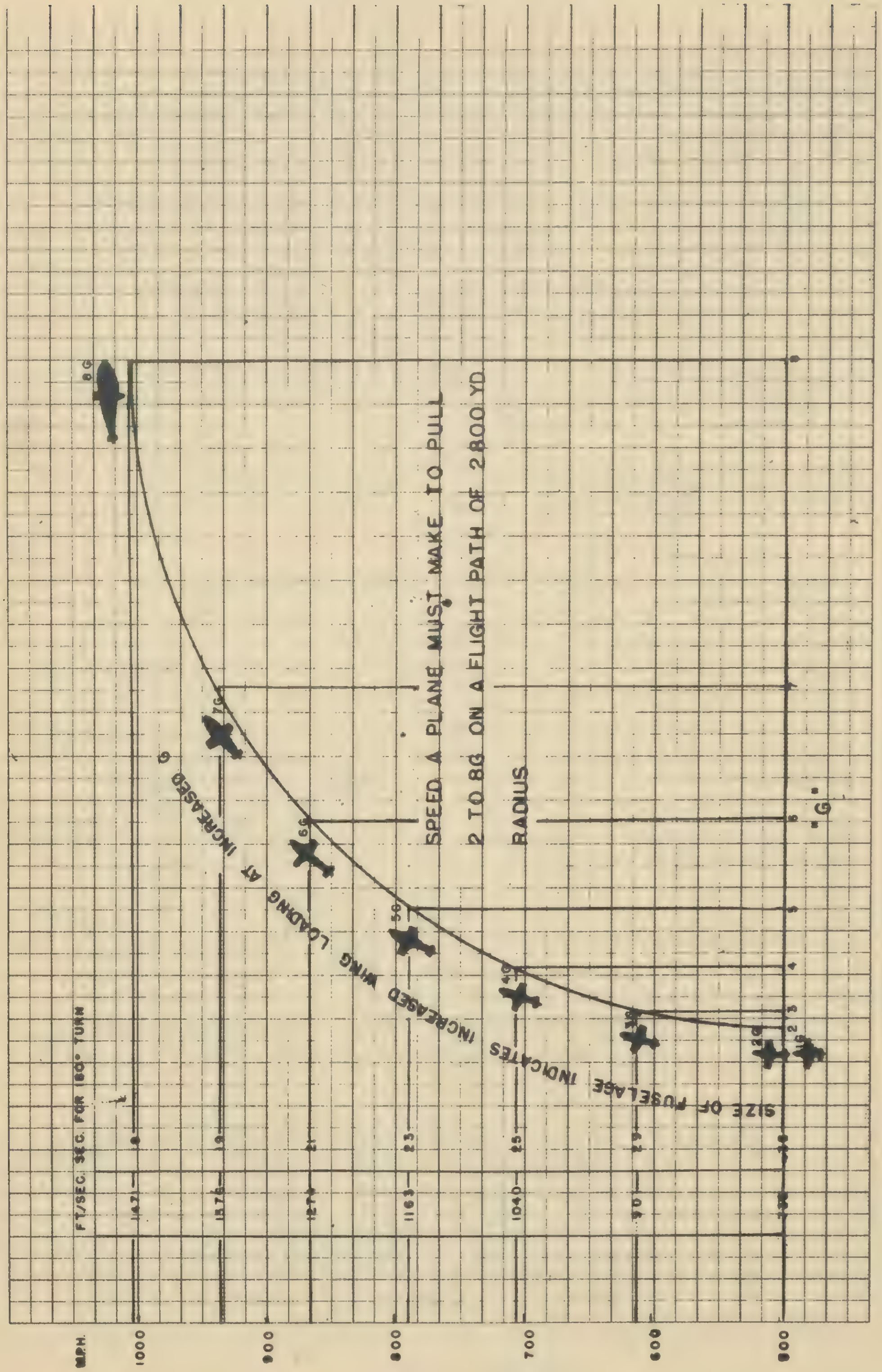

FIGURE 71

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the position of the pilot or a combination of such postural change with G suit would be indicated. A combination of present suits with seats which tilted to a semi-prone position during increased positive G might provide the necessary protection safely. This combination should be explored. It goes without saying that studies of the prone position and of the supine position not treated extensively because they are outside the scope of this report should continue.

3. It is recommended that the Aero Medical Laboratory, Engineering Division, ATSC, consider the feasibility of the combination of G suit and pressure suit for high altitude protection to allow the necessary pressurization of the body to perform two functions.

GLOSSARY
of terms and abbreviations commonly used in this report and peculiar to the field of acceleration

AAF G-1 (GPS) Gradient pressure suit. A multiple pressure pneumatic anti-G device.

AAF G-2 A single pressure pneumatic suit similar in general appearance to the AAF type G-1.

AAF G-3 and G-3A USN Z-3. Skeleton suit, cut-away suit. A single pressure pneumatic anti-G device.

AAF G-4 (US Navy Z-1, Z-2) A single pressure coverall pneumatic anti-G suit.

AOS Arterial occlusion suit (Clark-Wood suit). A pneumatic anti-G suit.

Average visual protection The average protection a G suit affords vision calculated by subtracting average G tolerance for clear vision, visual dimming and CLL without the suit from that with the suit.

Blackout Complete temporary loss of vision with preservation of consciousness.

CAAG Cotton aerodynamic anti-gravity suit. A multiple pressure pneumatic anti-G suit developed by Doctor Cotton of Sydney, Australia.

Centrifuge, human A laboratory device consisting of a rotating structure which applies centripetal acceleration (centrifugal force) to human subjects.

CLL Central lights lost. Loss of vision at the point of visual fixation.

Dim Visual dimming. Generalized dimming of vision without PLL.

Ear opacity tracing A photoelectric recording of the opacity of the ear to light which gives an indirect qualitative measure of the blood content of the ear.

Ear pulse tracing A photoelectric recording of pulsation of blood in the ear.

FFS Franks Flying Suit. The hydrostatic G suit developed by the RCAF.

G suit A garment designed to raise G tolerance by applying pressure to the body.

G valve G compensated, G activated air pressure regulating valve designed to meter air to the G suit during increased positive G.

G switch A G activated microswitch.

G tolerance The G to which a subject must be exposed to produce a given symptom.

G unit A unit used for measuring the magnitude of acceleration. One G denotes an acceleration of 32.2 feet per second^2 (9.8 m./sec.^{2}), the acceleration produced by the force of gravity.

Hydrodynamic G suits G suits which use the increased hydrostatic pressure developed in a column of liquid during increased G to apply pressure to the body.

<u>KOP</u> Kelly one piece suit. A pneumatic anti-G suit developed by the RAAF.

<u>PLL</u> Peripheral lights lost. Loss of peripheral vision beyond an arc of 46 degrees, the center of which is at the eyes.

<u>PLS</u> Pneumatic G suit which applies pressure by the capstan principle.

<u>Pneumodynamic G suits</u> G suits which utilize air under pressure to apply pressure to the body

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